



Jet Propulsion Laboratory
California Institute of Technology

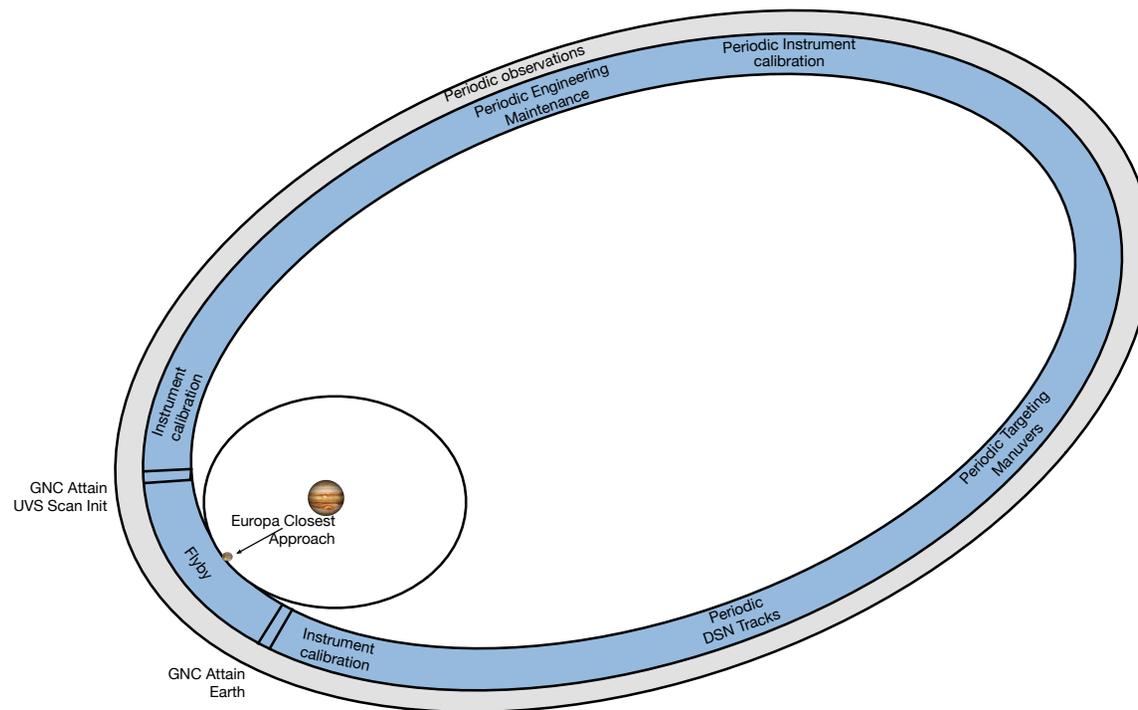
Autonomous Science Restart for the Planned Europa Mission with Lightweight Planning and Execution

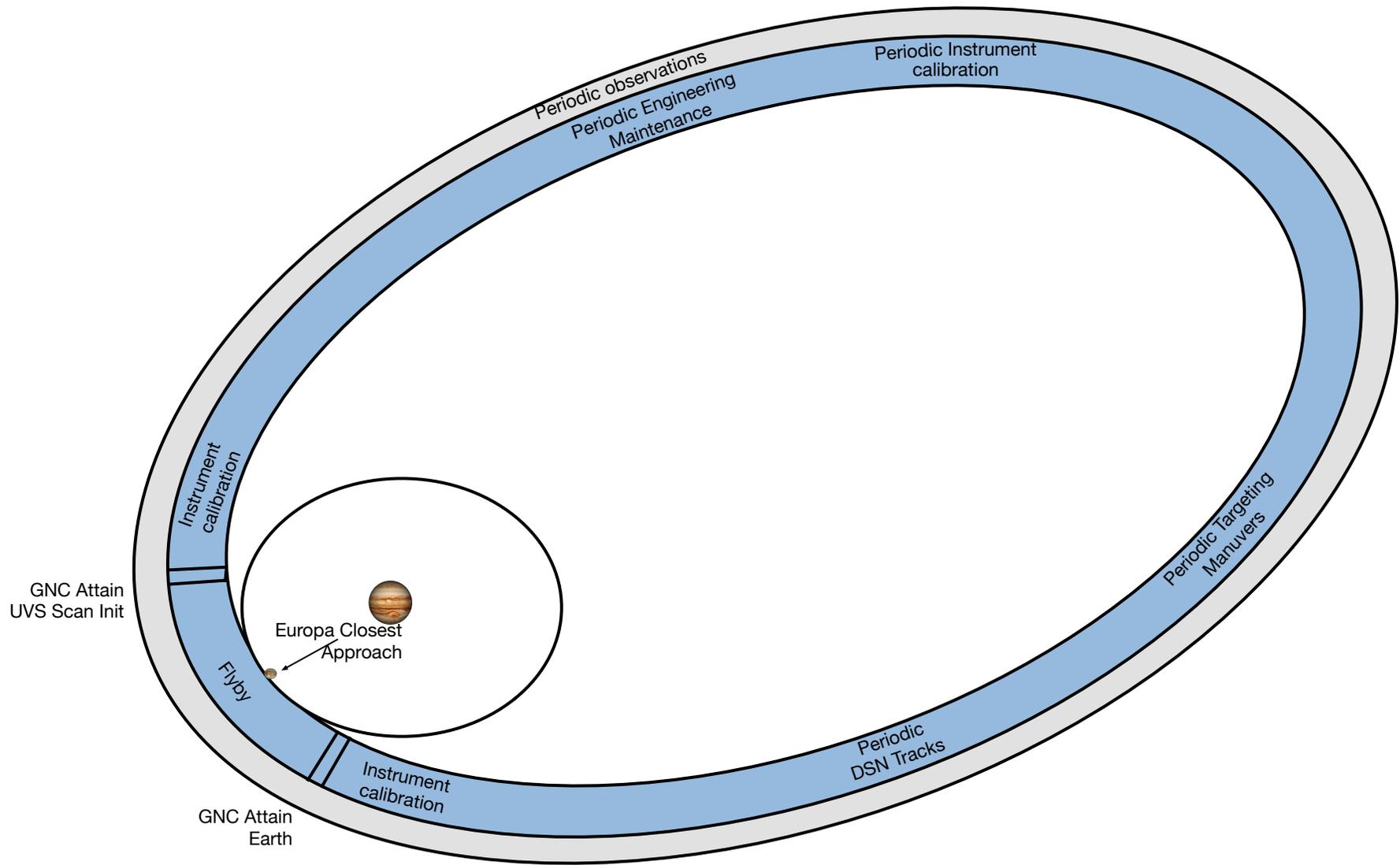
Dan Gaines, Vandi Verma Gregg Rabideau, Steve Schaffer, Rajeev Joshi
Jet Propulsion Laboratory, California Institute of Technology
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06/17/2017

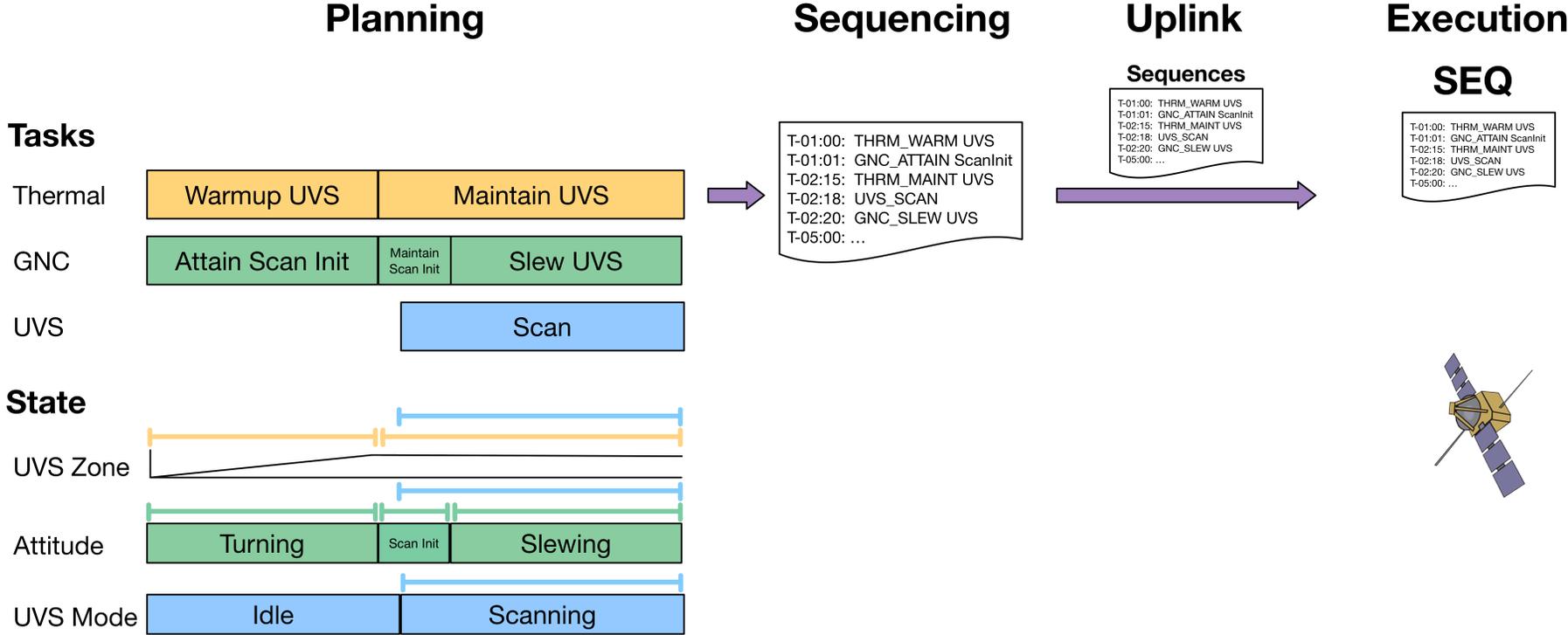
EUROPA FLYBY RESTART SCENARIO

- There are ~45 flybys that the Planned Europa Mission is base-lined to perform.
- Each flyby would be ~10-20 hrs as part of an orbit of ~14 days.
- Requirement is to accommodate 5 FSW resets during flyby segment.
- Highest priority science would occur during the flyby. Requirement to recover science post reset.





SEQUENCING APPROACH

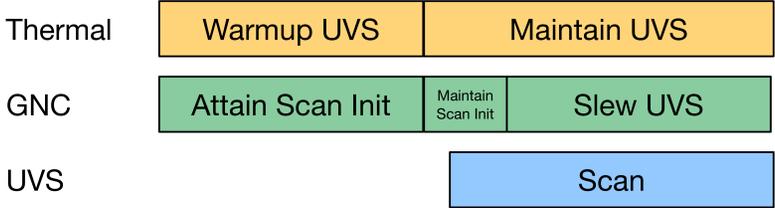


SEQUENCING APPROACH

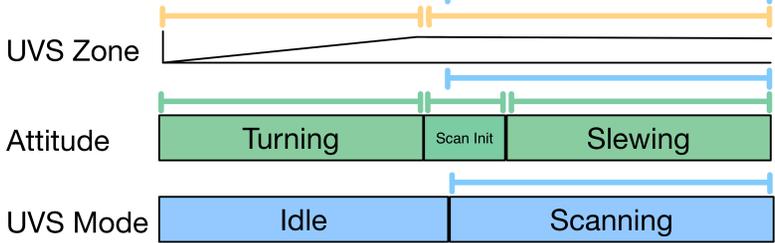
Intent and Constraints

Planning

Tasks



State



Sequencing

```

T-01:00: THRM_WARM UVS
T-01:01: GNC_ATTAIN ScanInit
T-02:15: THRM_MAINT UVS
T-02:18: UVS_SCAN
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T-05:00: ...
    
```



Uplink

Sequences

```

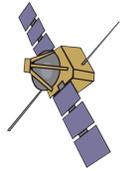
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SEQUENCING APPROACH

Intent and Constraints

Planning

Tasks

Thermal



GNC



UVS



State

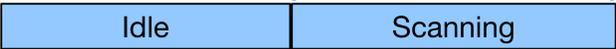
UVS Zone



Attitude



UVS Mode



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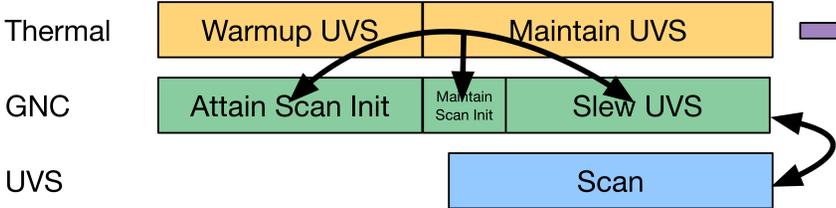


SEQUENCING APPROACH

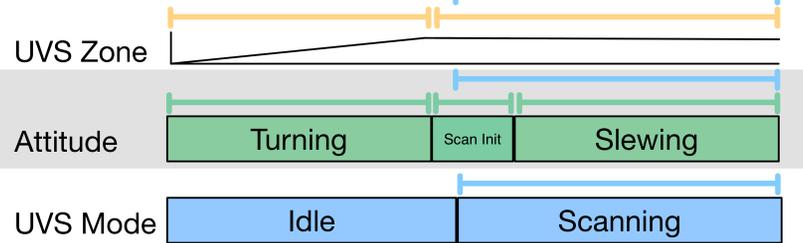
Intent and Constraints

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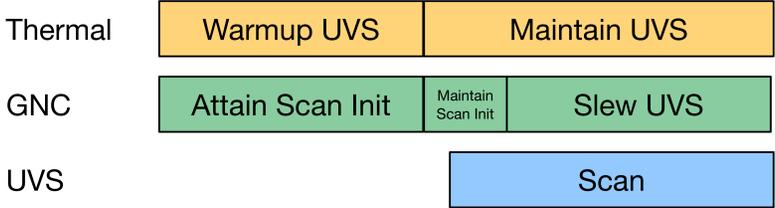


SEQUENCING APPROACH

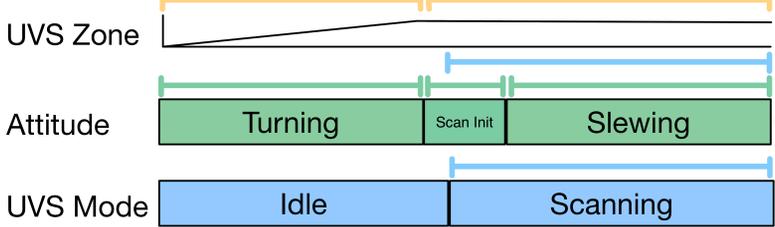
Intent and Constraints

Planning

Tasks



State



Model using predicted state

Sequencing

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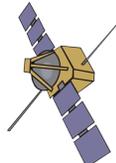
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SEQUENCING APPROACH

Intent and Constraints

Planning

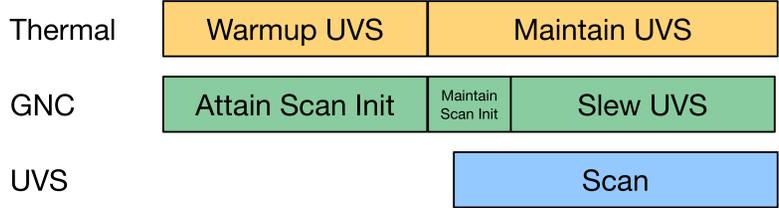
One (or few) possible plan paths.

Sequencing

Uplink

Execution

Tasks

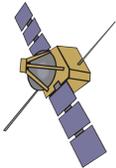


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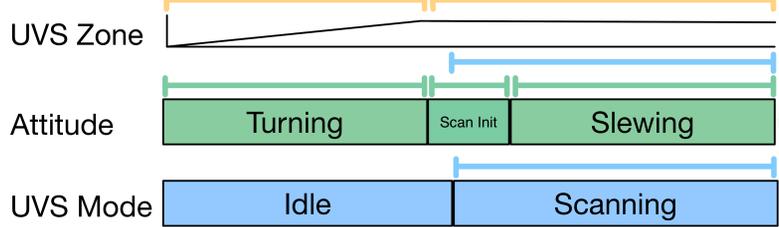
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State



Model using predicted state

SEQUENCING APPROACH

One (or few) possible plan paths.

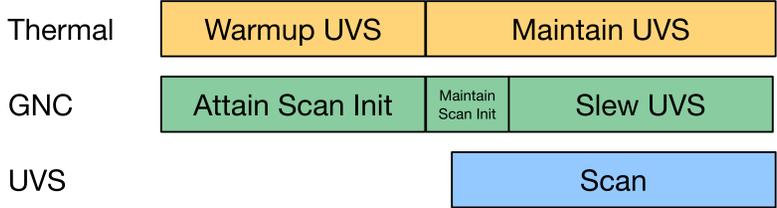
Planning

Sequencing

Uplink

Execution

Tasks

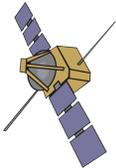


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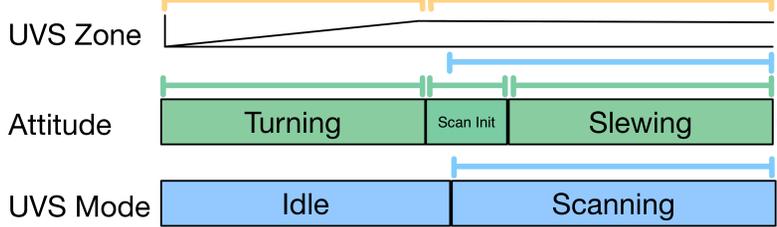
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Model using predicted state

SEQUENCING APPROACH

One (or few) possible plan paths.

Monitoring limited to fault checking

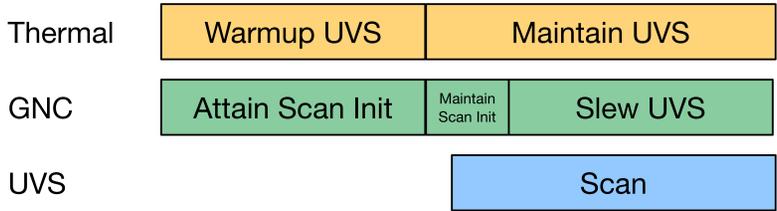
Planning

Sequencing

Uplink

Execution

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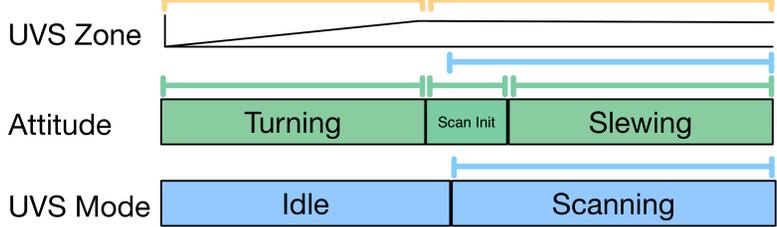
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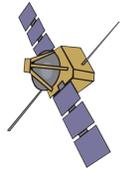
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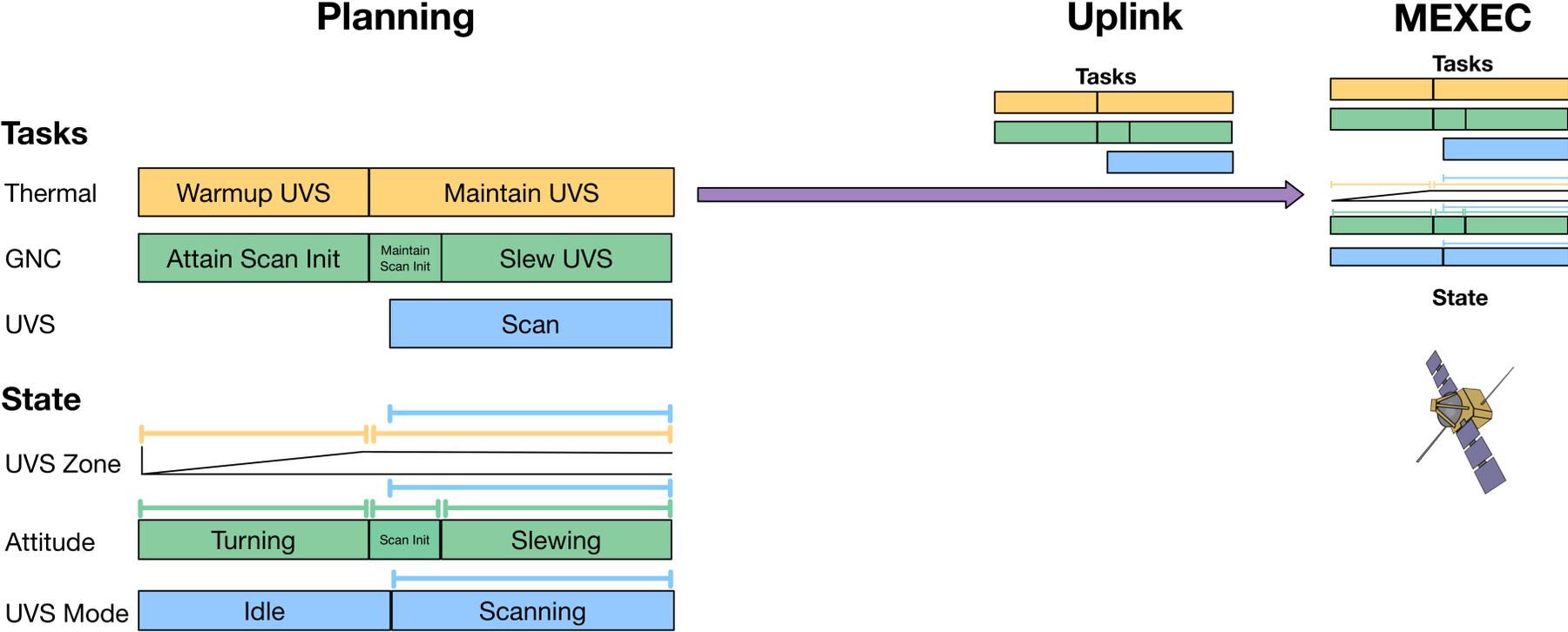
State



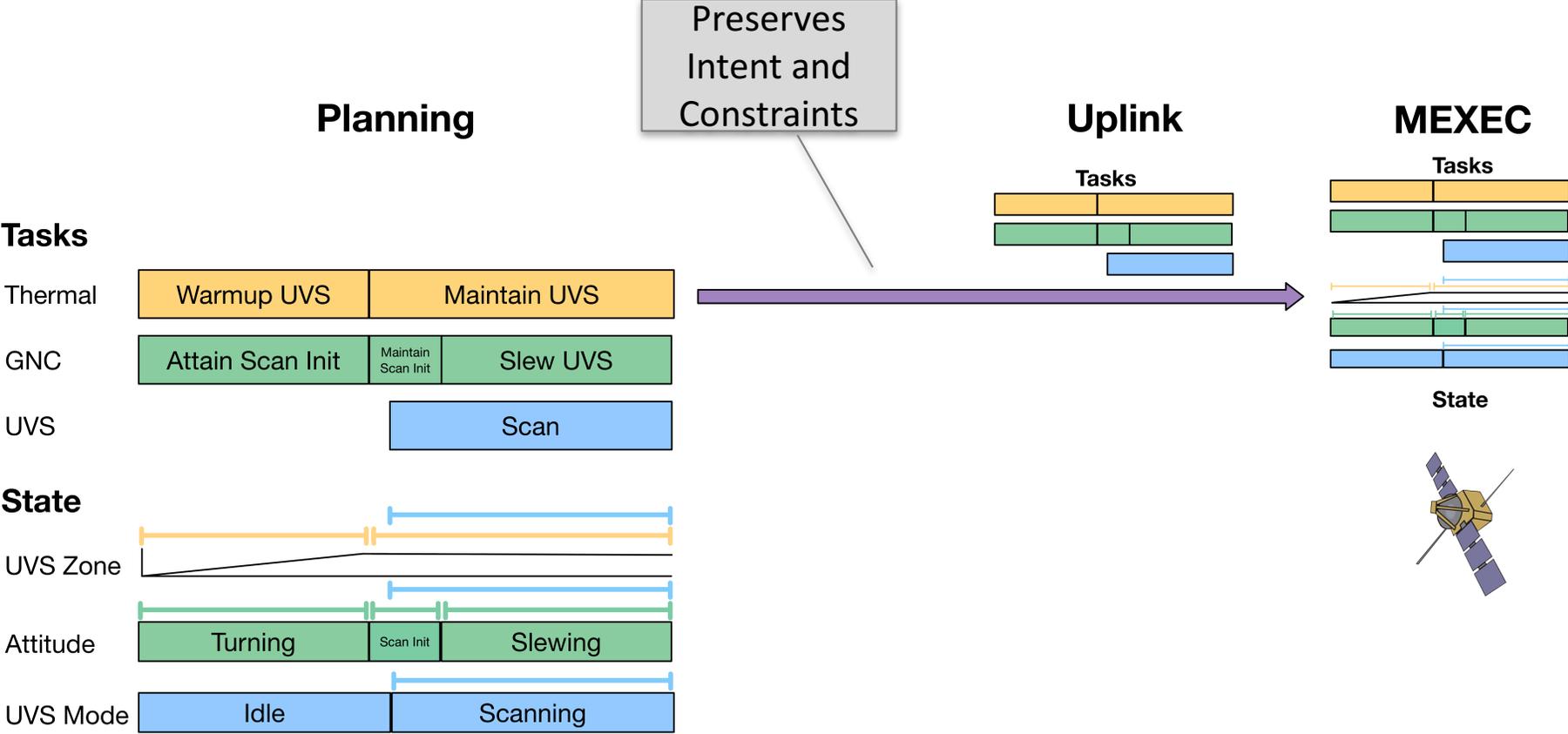
Model using predicted state



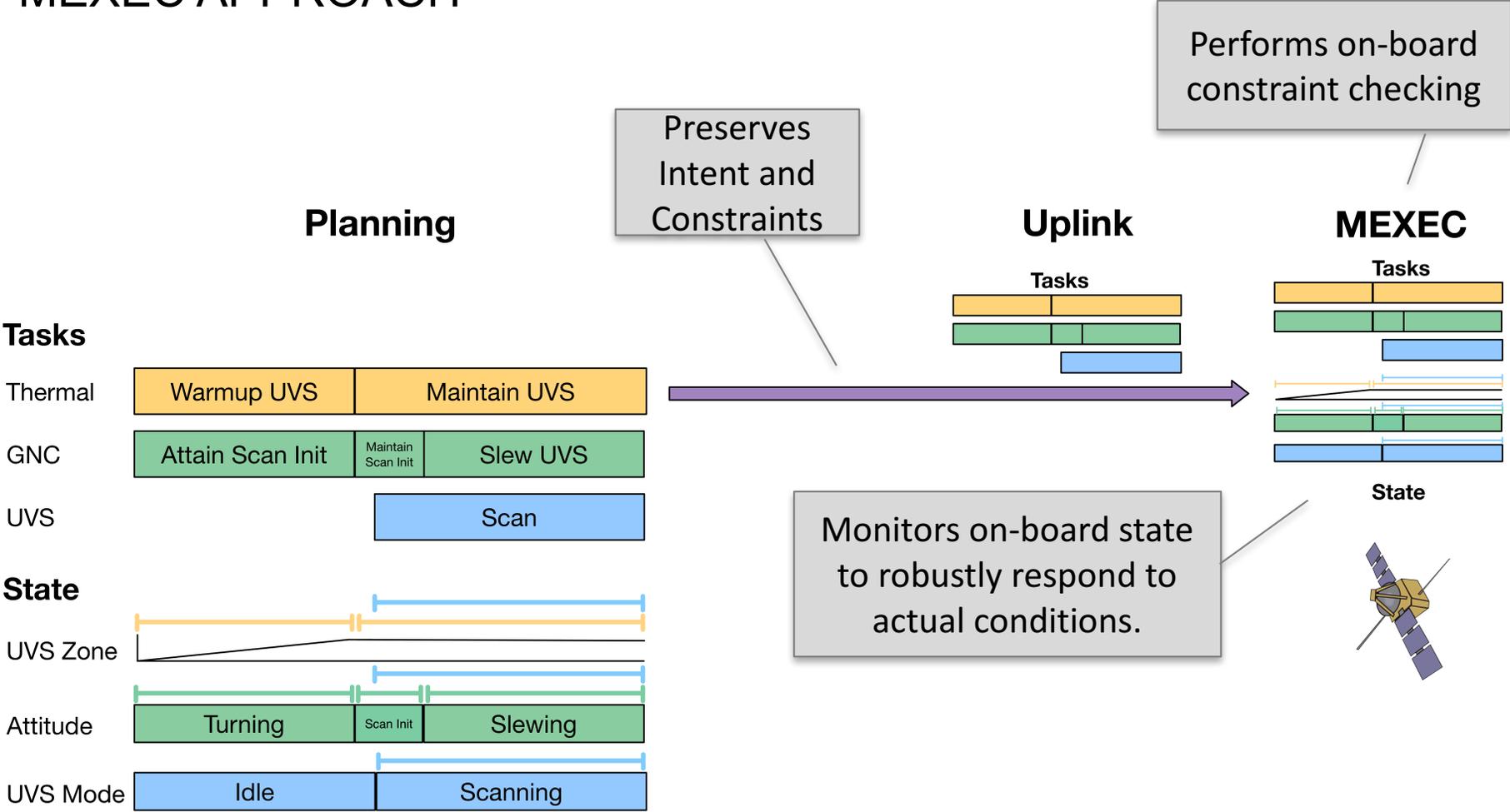
MEXEC APPROACH



MEXEC APPROACH



MEXEC APPROACH



MEXEC OVERVIEW

- Coordinates spacecraft activities based on on-board state and specified intent
 - Monitors and projects spacecraft state to coordinate the execution of activities
 - Currently executing activities
 - Future activities in the plan
- Key Benefits
 - Robustly respond to actual state
 - Performs on-board constraint checking for executing and remaining plan
 - Enables fail operational capability (e.g. after FSW reset)
 - Allows opportunistically taking advantage of surplus resources
 - Simplifies uplink product creation and review
 - Intent and constraints explicitly captured
 - Reduces tactical overhead of command product generation
 - Flexible choice between sequencing and commanding with higher level intent
 - A task can represent a sequence
 - Allows leveraging of existing sequencing capability
 - Simplifies sequence creation by decoupling sub-system interactions from sequencing
 - Sub-system interactions managed via constraints

EXAMPLE: NOMINAL INSTRUMENT SCENARIO

10:00 10:15 10:30 10:33 10:40 11:05



Initial Seed Plan:
10:00 Gnc_Attain NADIR
10:15 Instrument Flyby Request

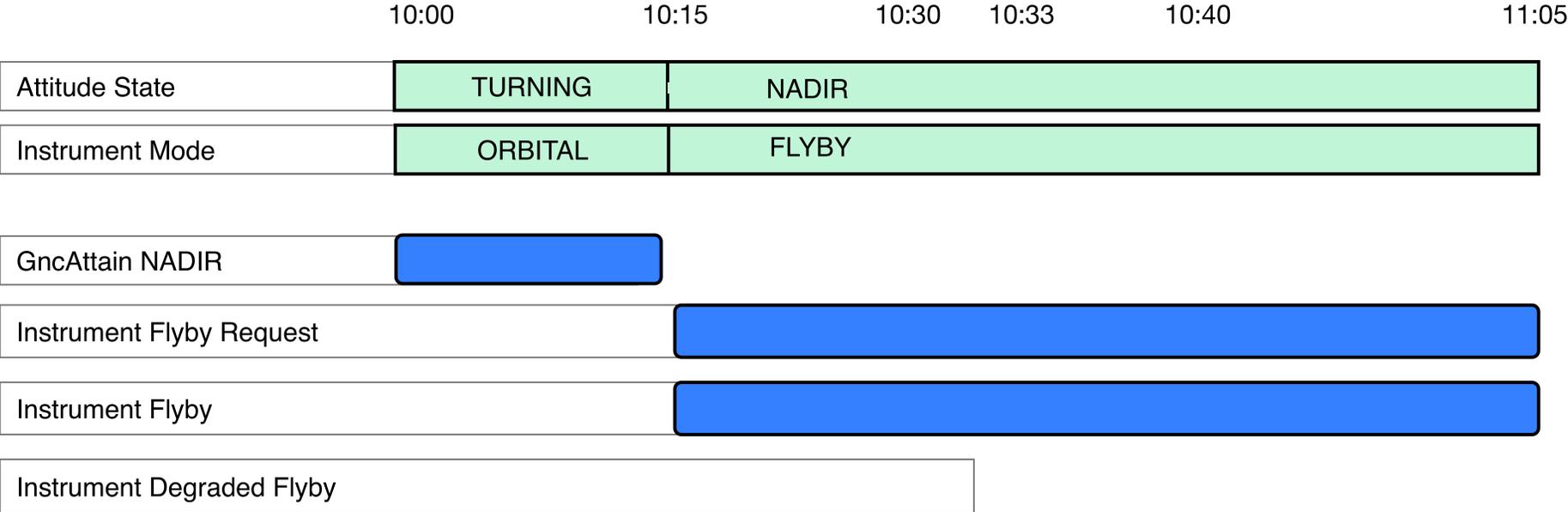
EXAMPLE: NOMINAL INSTRUMENT SCENARIO

10:00 10:15 10:30 10:33 10:40 11:05



Initial seed plan task

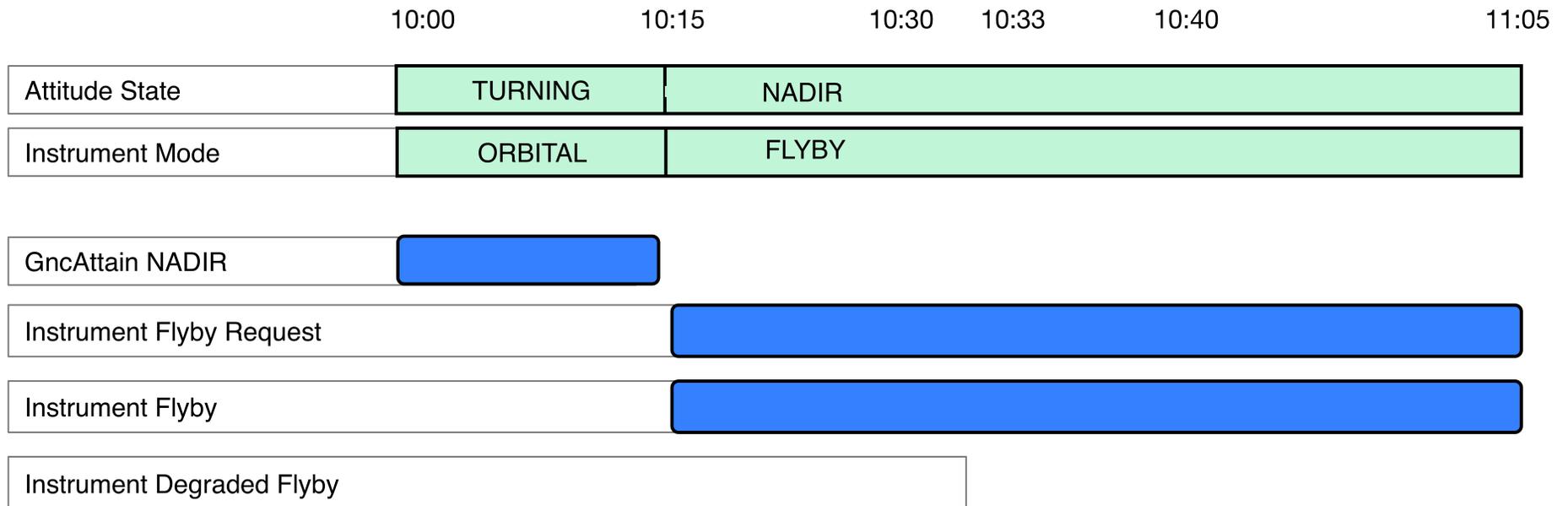
EXAMPLE: NOMINAL INSTRUMENT SCENARIO



Initial seed plan task

SBS state

EXAMPLE: TASK CONSTRAINTS AND IMPACTS

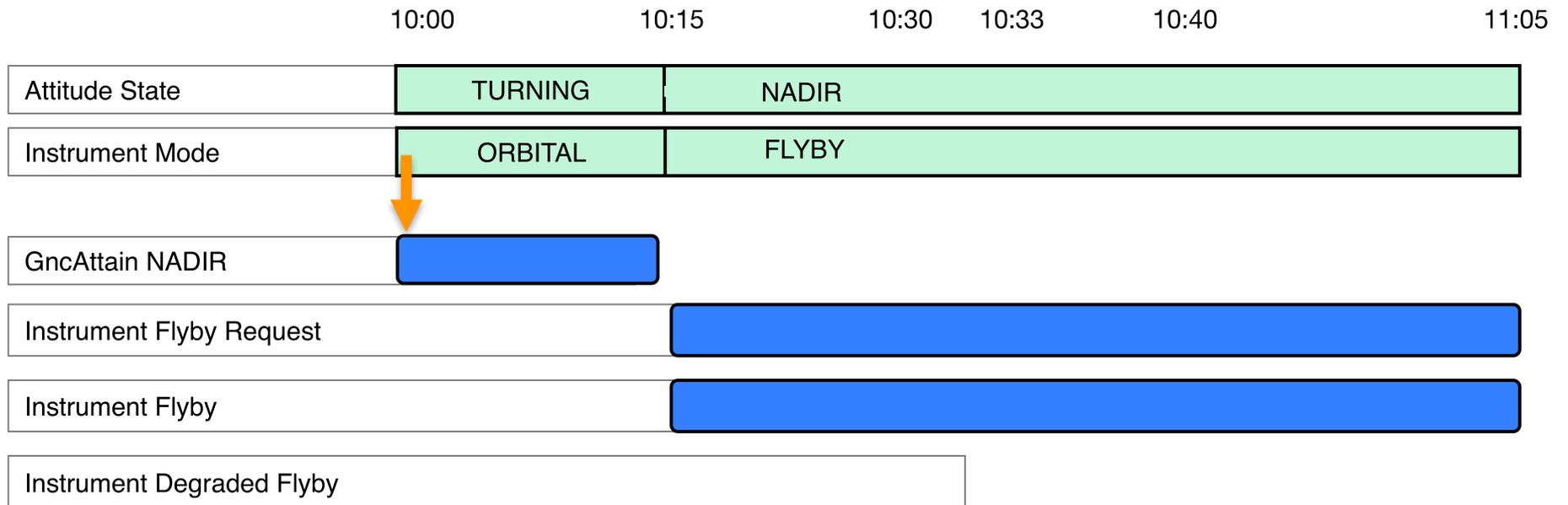


Initial seed plan task

SBS state

- **Constraint:** Requirement on state (resource) value at a specific time, or over a time interval
- **Impact:** A change in state (resource) value at a specific time, or over a time interval: Value assignment, value increment, rate increment.
- **Resource:** a value over time (e.g. time/duration, data volume, energy, claims, states, etc).

EXAMPLE: NOMINAL INSTRUMENT SCENARIO (PRE)

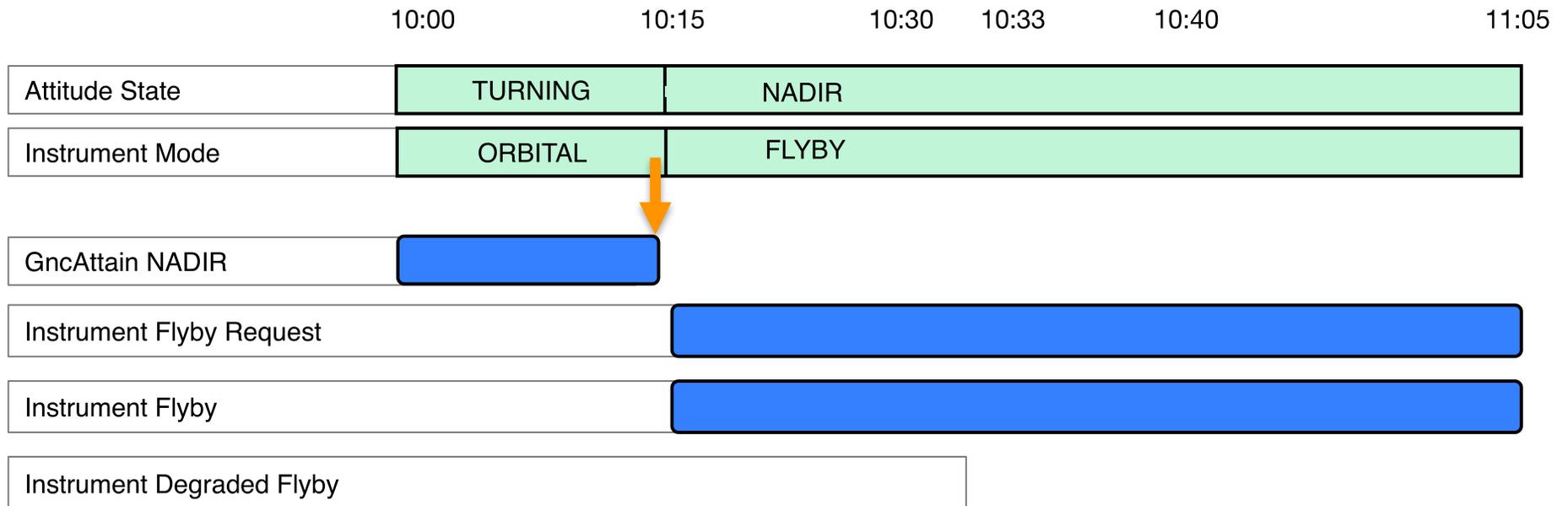


Initial seed plan task

SBS state

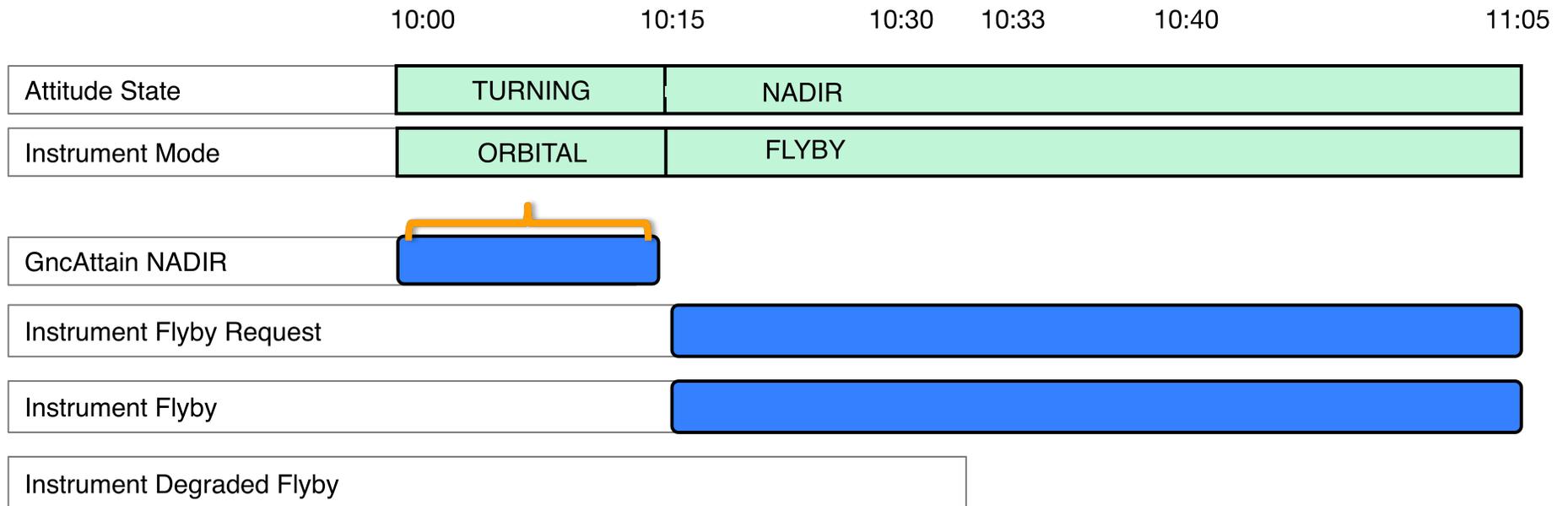
- **Constraint:** Requirement on state (resource) value at a specific time, or over a time interval
- **Impact:** A change in state (resource) value at a specific time, or over a time interval

EXAMPLE: NOMINAL INSTRUMENT SCENARIO (POST)



- **Constraint:** Requirement on state (resource) value at a specific time, or over a time interval
- **Impact:** A change in state (resource) value at a specific time, or over a time interval

EXAMPLE: NOMINAL INSTRUMENT SCENARIO (DURING)

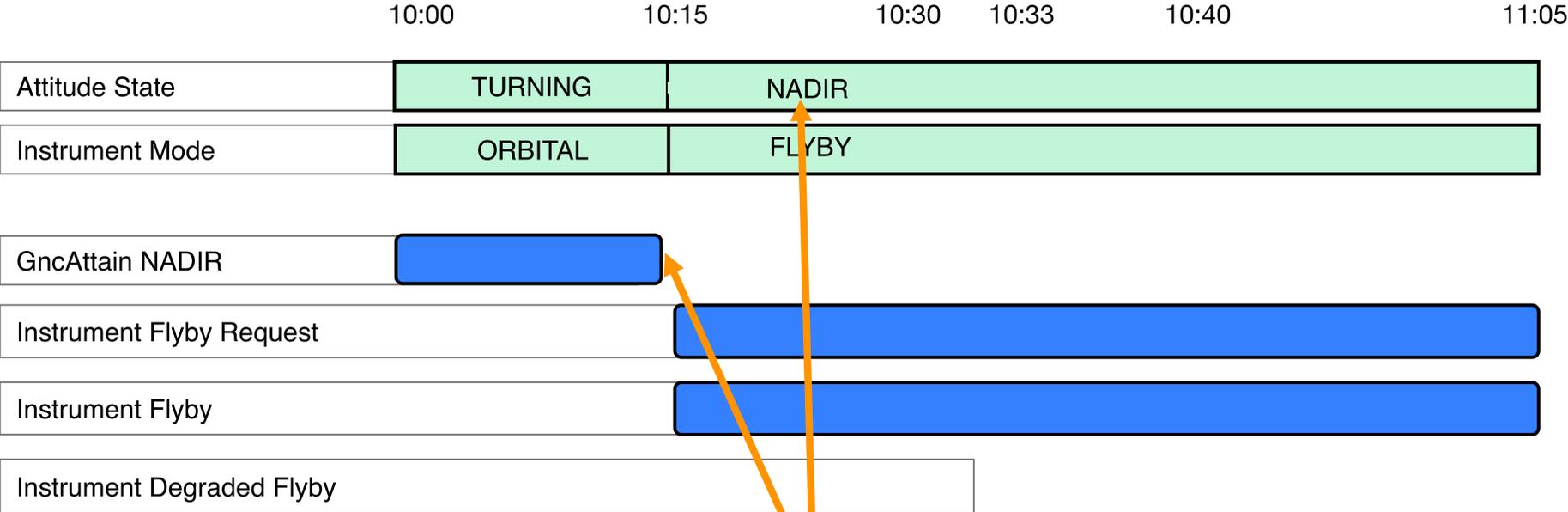


Initial seed plan task

SBS state

- **Constraint:** Requirement on state (resource) value at a specific time, or over a time interval
- **Impact:** A change in state (resource) value at a specific time, or over a time interval

EXAMPLE: NOMINAL INSTRUMENT SCENARIO



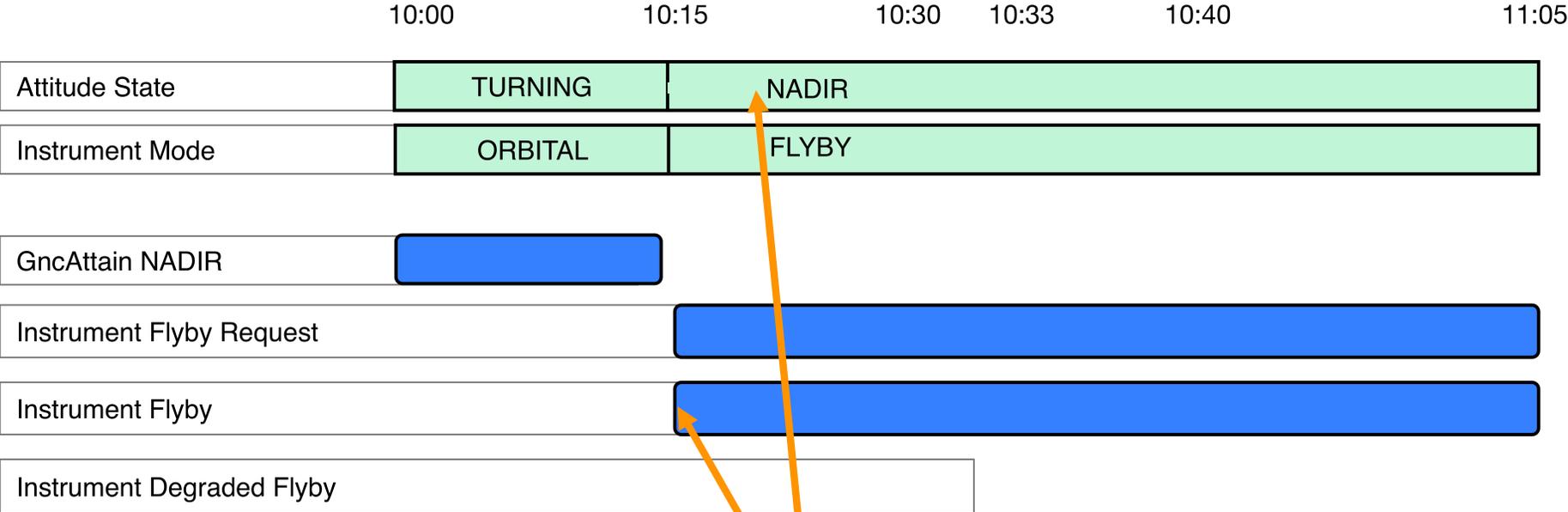
Example Task Constraints/Impacts:

Gnc Attain NADIR:	POST IMPACT	Attitude State=NADIR
Instrument Flyby:	PRE CONSTRAINT MAINTAIN CONSTRAINT DURING IMPACT	Attitude State = NADIR Attitude State = NADIR Satisfies InstrumentFlybyRequest
Instrument Degraded Flyby :	DURING IMPACT	Satisfies InstrumentFlybyRequest

Example Contingency Response:
Restart InstrumentFlyby on failure

Example Plan Modifiers to resolve violation:
Add GncAttain NADIR
Add Degraded Flyby
Remove InstrumentFlyby

EXAMPLE: NOMINAL INSTRUMENT SCENARIO



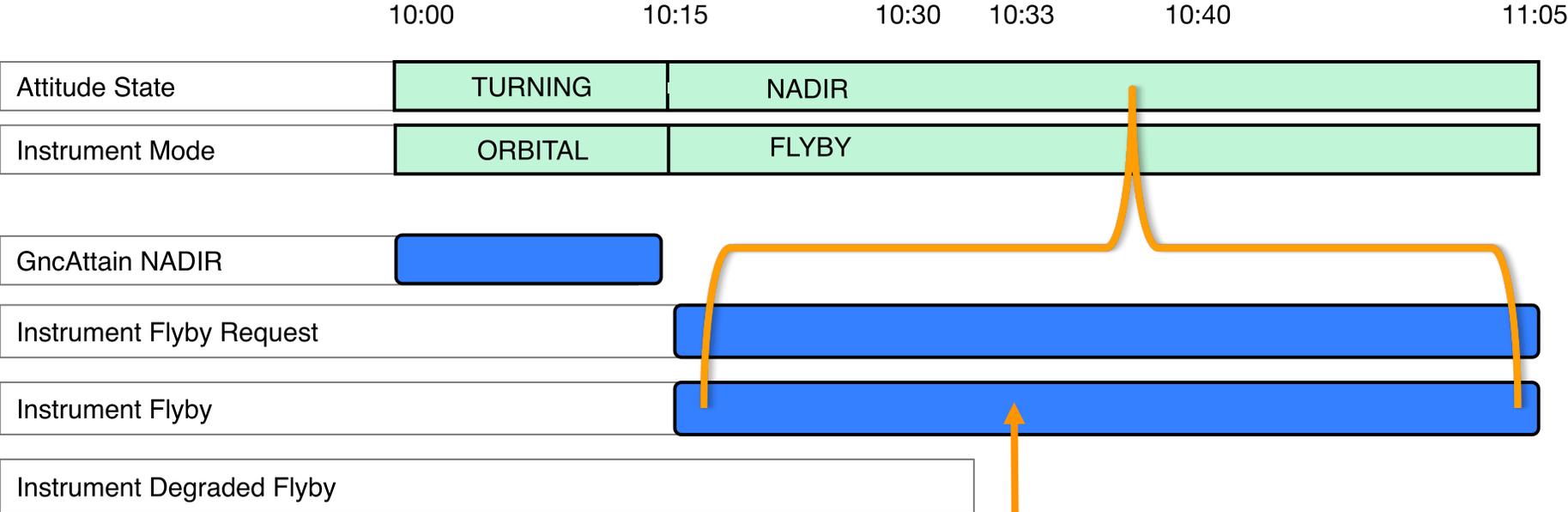
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	MAINTAIN CONSTRAINT	Attitude State = NADIR
	DURING IMPACT	Satisfies InstrumentFlybyRequest
Instrument Degraded Flyby :	DURING IMPACT	Satisfies InstrumentFlybyRequest

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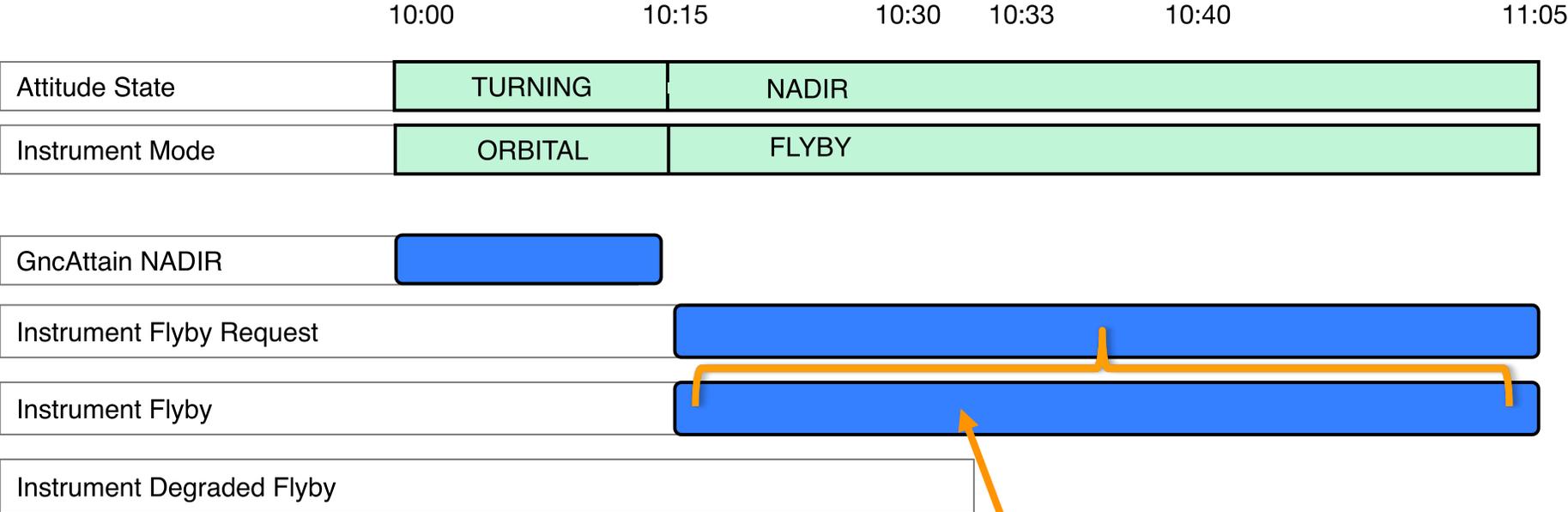
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EXAMPLE: NOMINAL INSTRUMENT SCENARIO



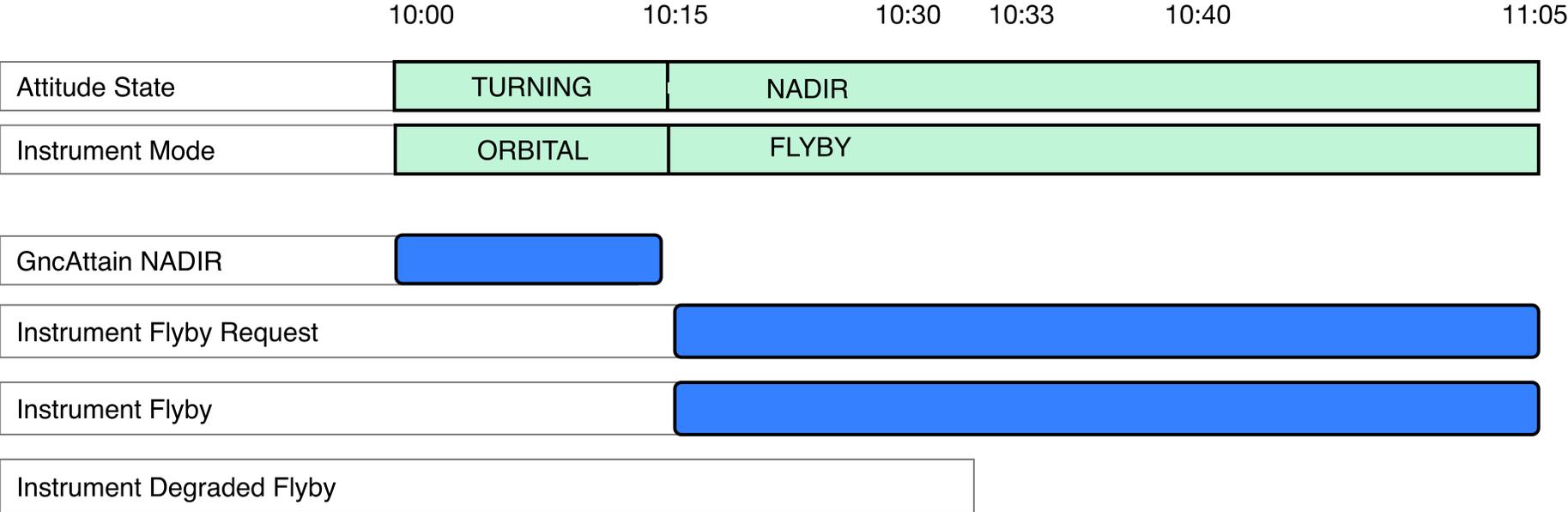
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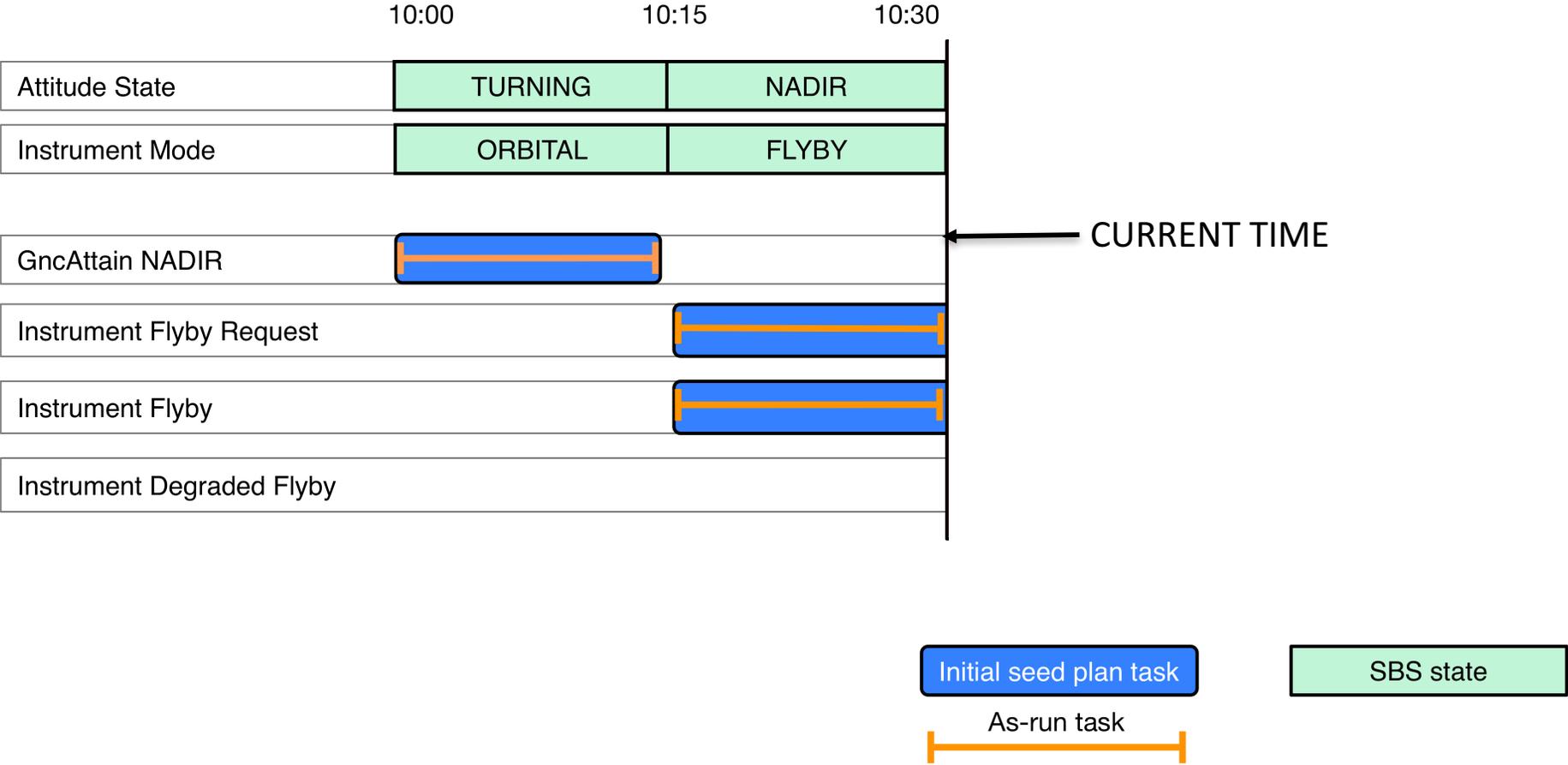
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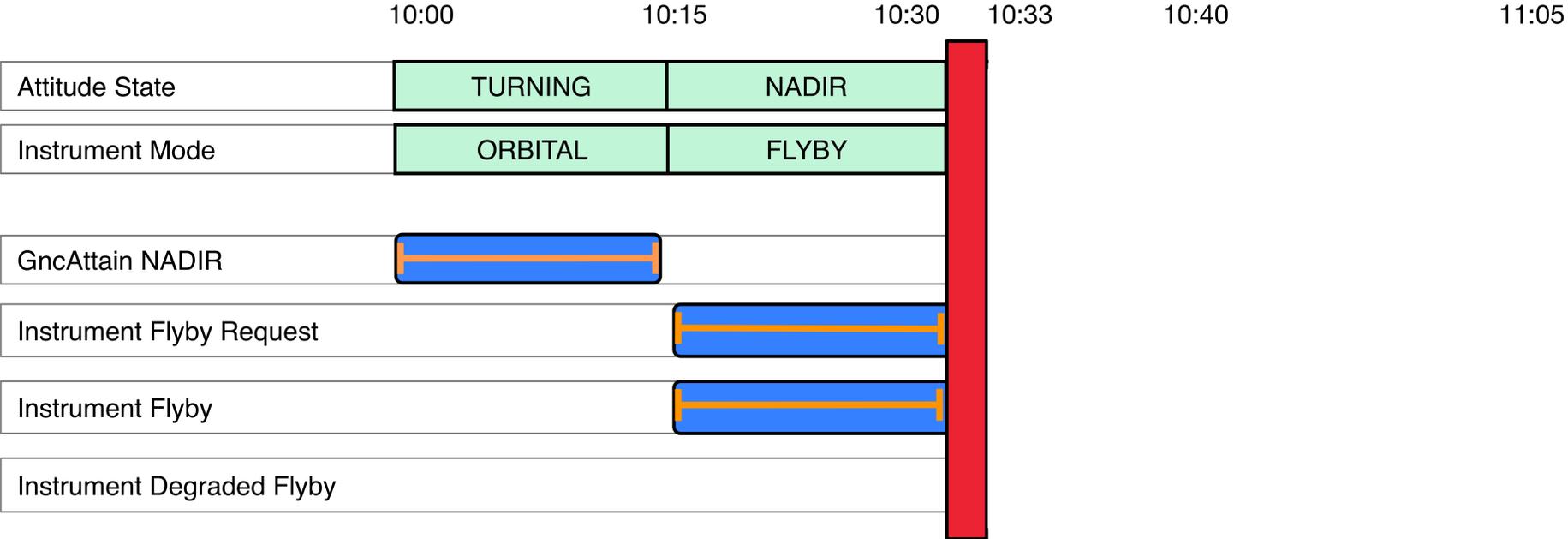
Initial seed plan task

SBS state

EXAMPLE: PARTLY EXECUTED INSTRUMENT SCENARIO



EXAMPLE: RESET



Initial seed plan task

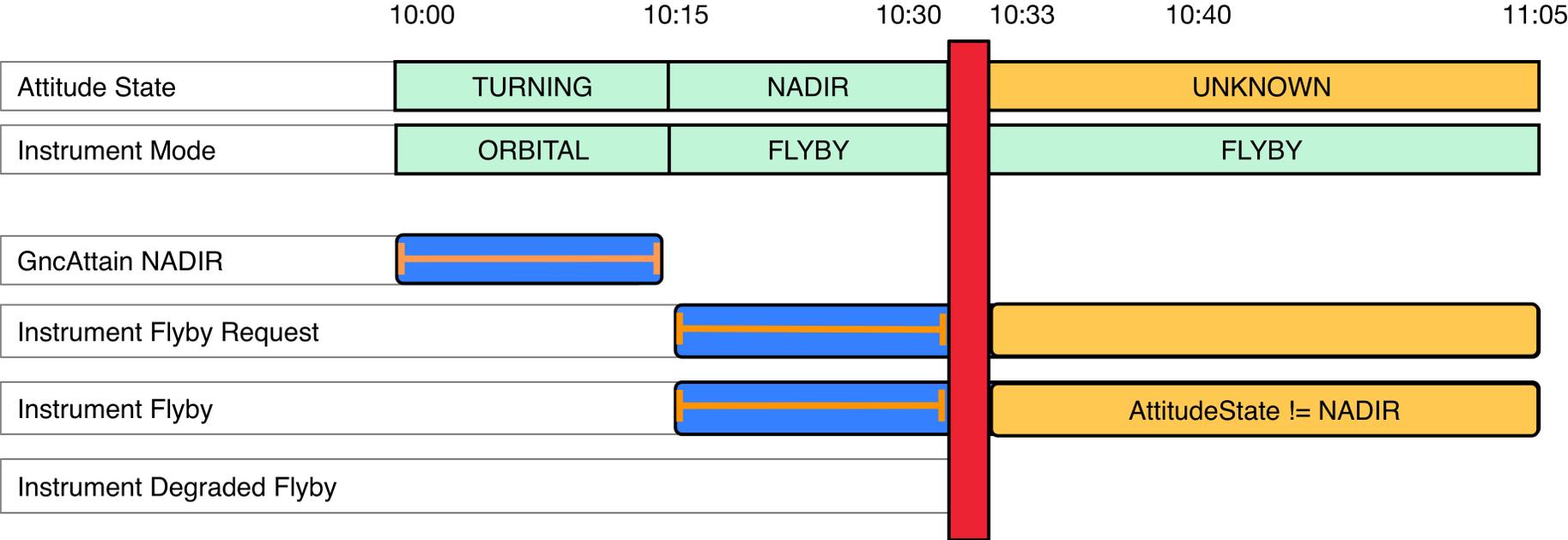
As-run task

SBS state

Reset duration

SFP restarts MEXEC at the end of reset.

EXAMPLE: RESET

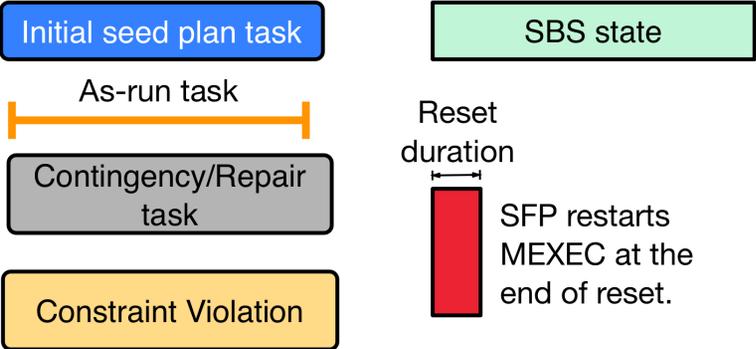


Example Task Constraints/Impacts:

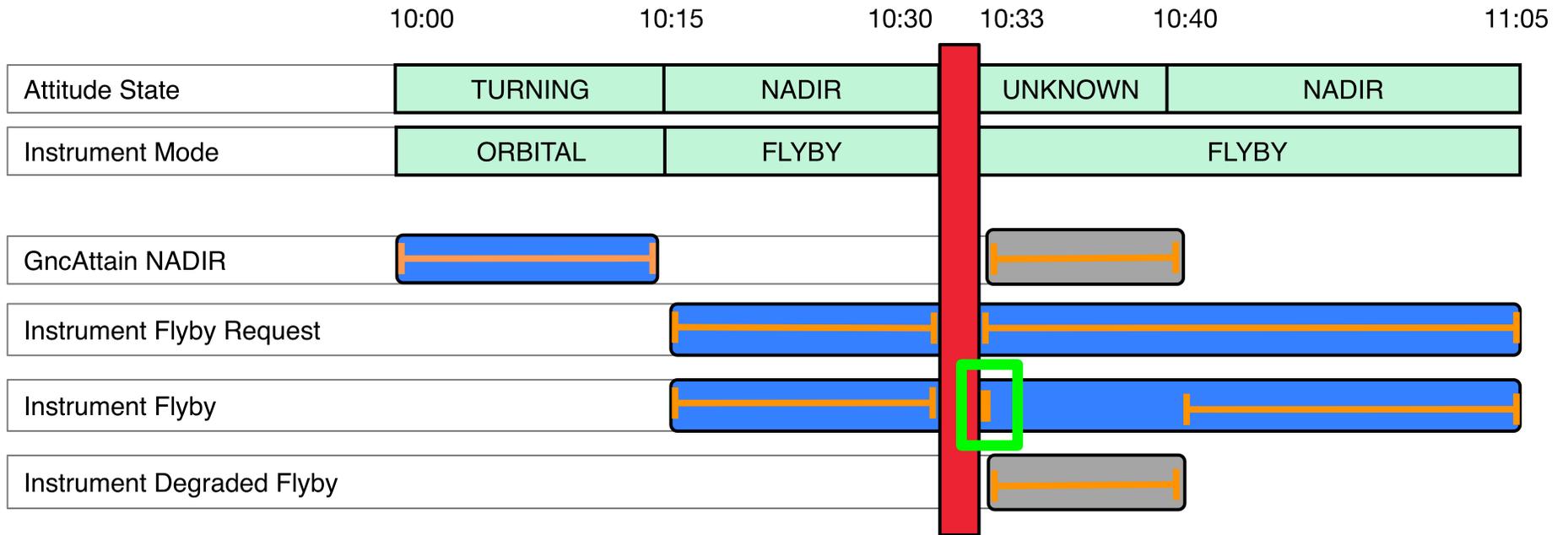
Gnc Attain NADIR:	POST IMPACT	Attitude State=NADIR
Instrument Flyby:	PRF CONSTRAINT	Attitude State = NADIR
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Remove InstrumentFlyby



EXAMPLE: RESPONSE TO EARLY RESET

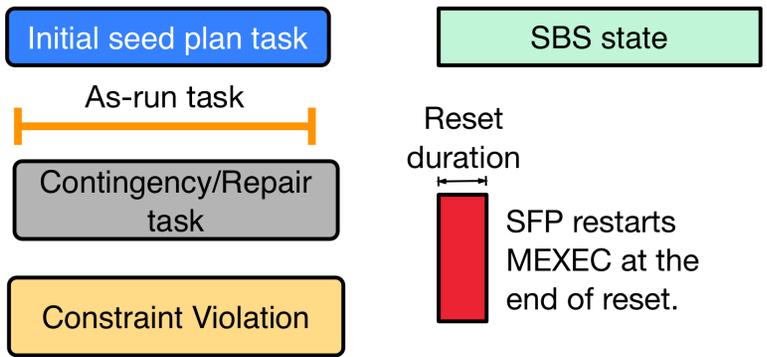


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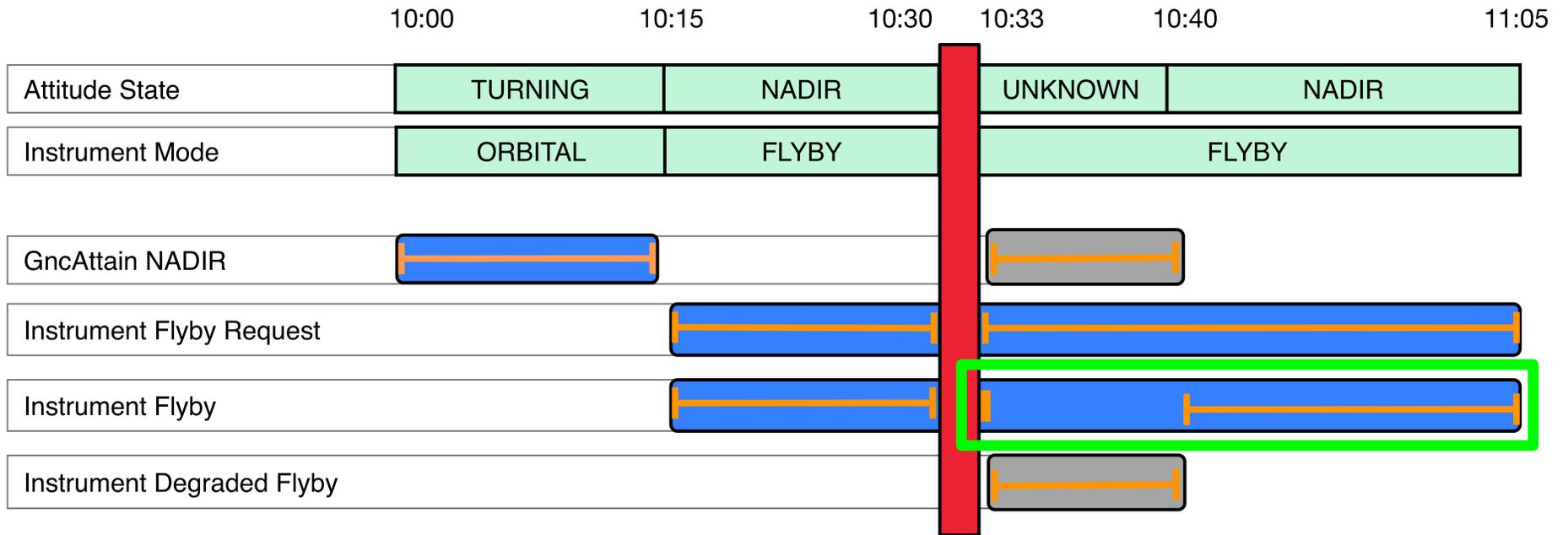
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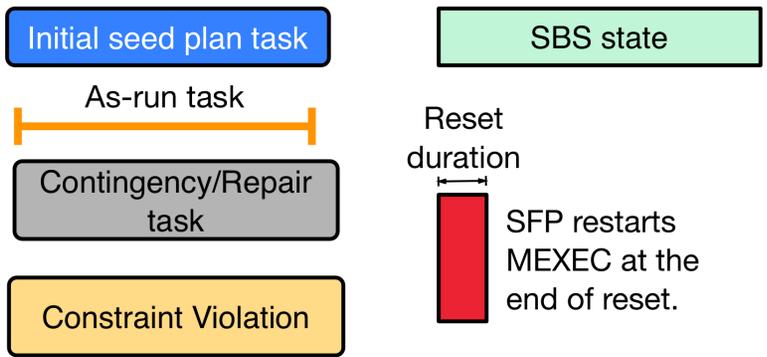


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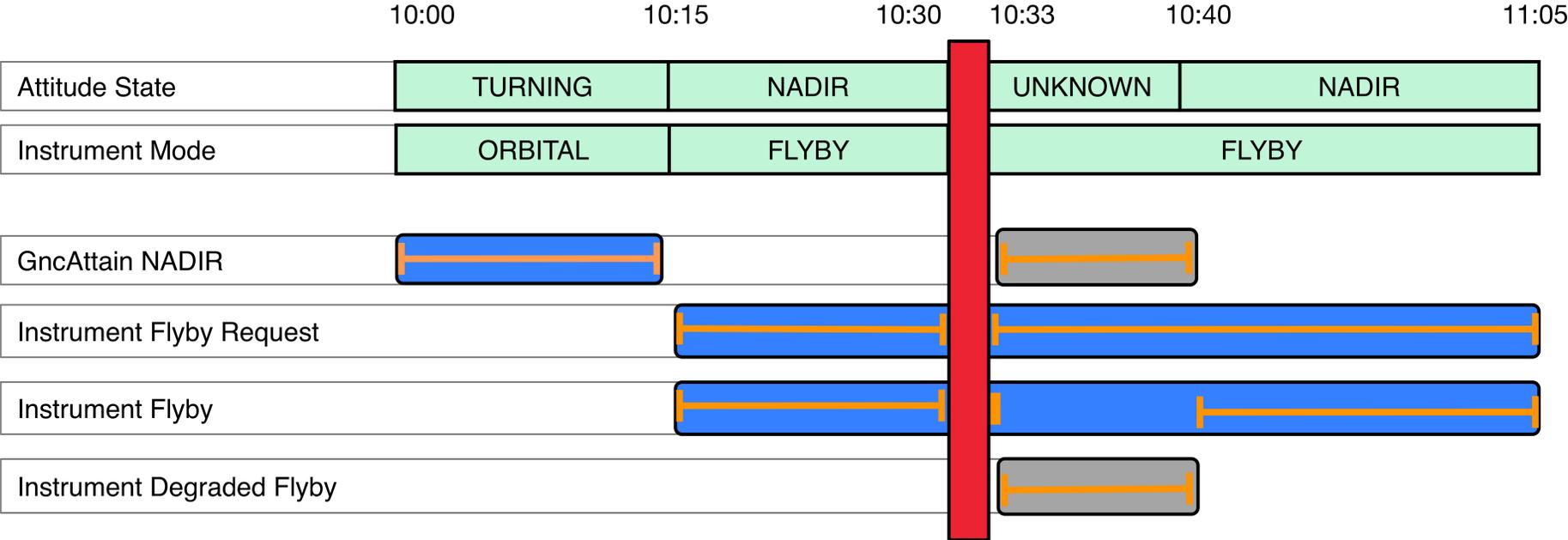
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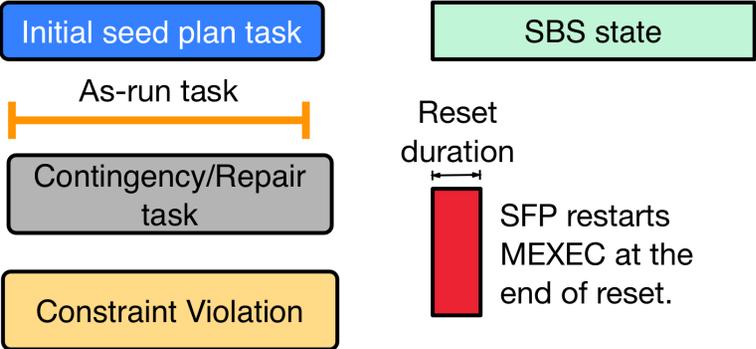


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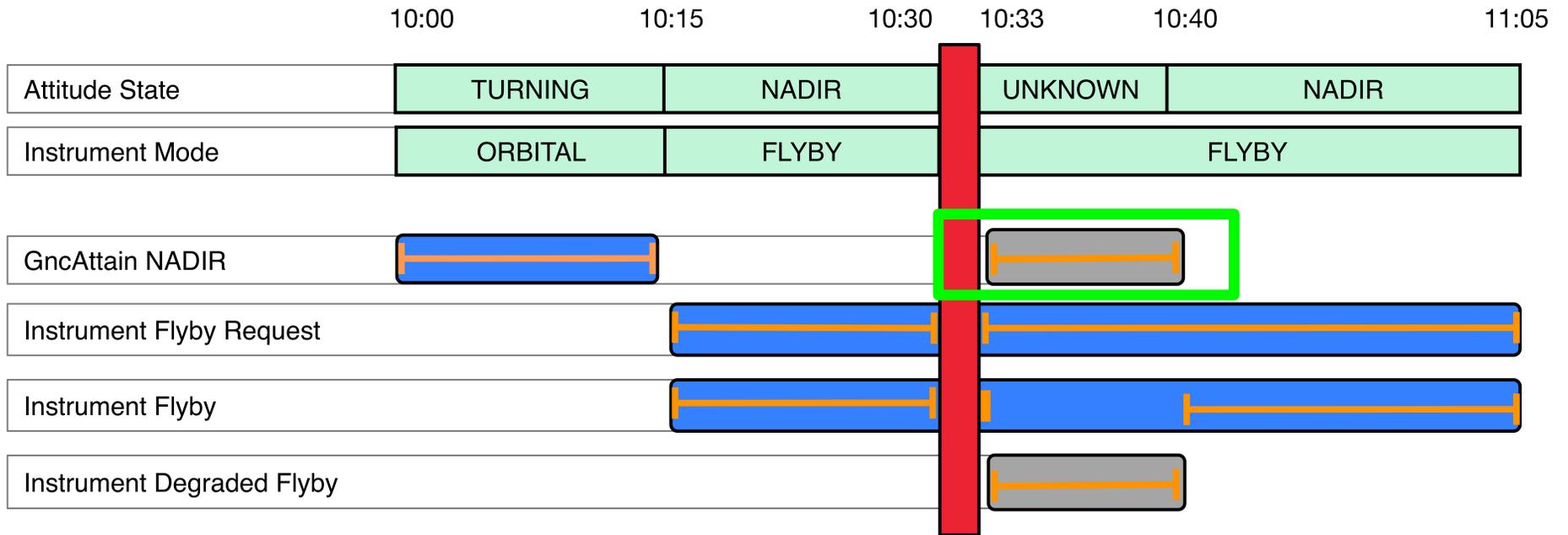
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Instrument Flyby:	PRE CONSTRAINT	Attitude State = NADIR
	MAINTAIN CONSTRAINT	Attitude State = NADIR
	DURING IMPACT	Satisfies InstrumentFlybyRequest
Instrument Degraded Flyby :	DURING IMPACT	Satisfies InstrumentFlybyRequest

Example Contingency Response:
Restart InstrumentFlyby on failure

Example Plan Modifiers to resolve violation:
Add GncAttain NADIR
Add Degraded Flyby
Remove InstrumentFlyby



EXAMPLE: RESPONSE TO EARLY RESET



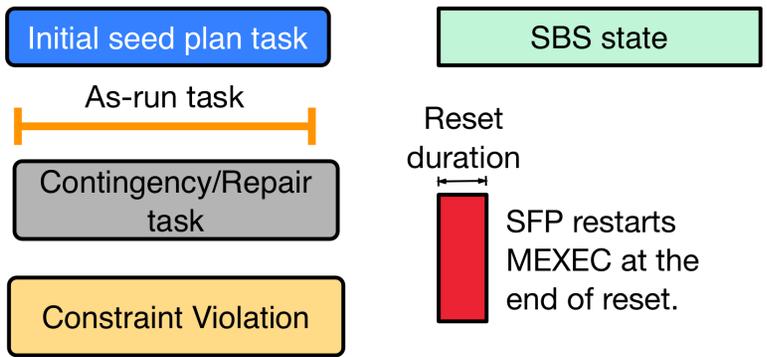
Example Task Constraints/Impacts:

Gnc Attain NADIR:	POST IMPACT	Attitude State=NADIR
Instrument Flyby:	PRE CONSTRAINT MAINTAIN CONSTRAINT DURING IMPACT	Attitude State = NADIR Attitude State = NADIR Satisfies InstrumentFlybyRequest
Instrument Degraded Flyby :	DURING IMPACT	Satisfies InstrumentFlybyRequest

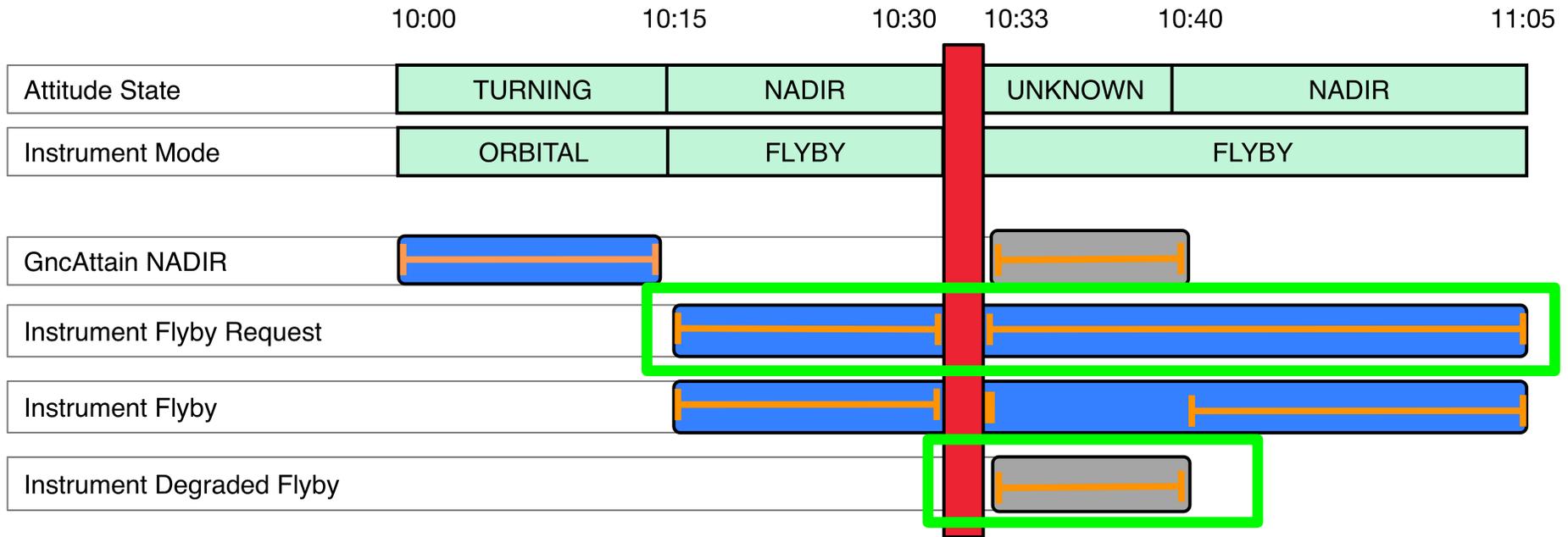
Example Contingency Response:
Restart InstrumentFlyby on failure

Example Plan Modifiers to resolve violation:

- Add GncAttain NADIR
- Add Degraded Flyby
- Remove InstrumentFlyby



EXAMPLE: RESPONSE TO EARLY RESET

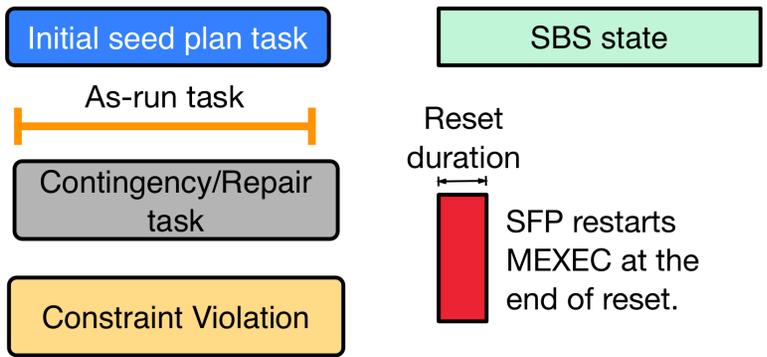


Example Task Constraints/Impacts:

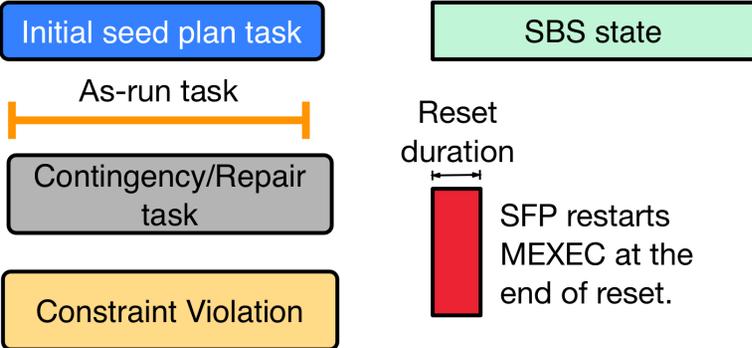
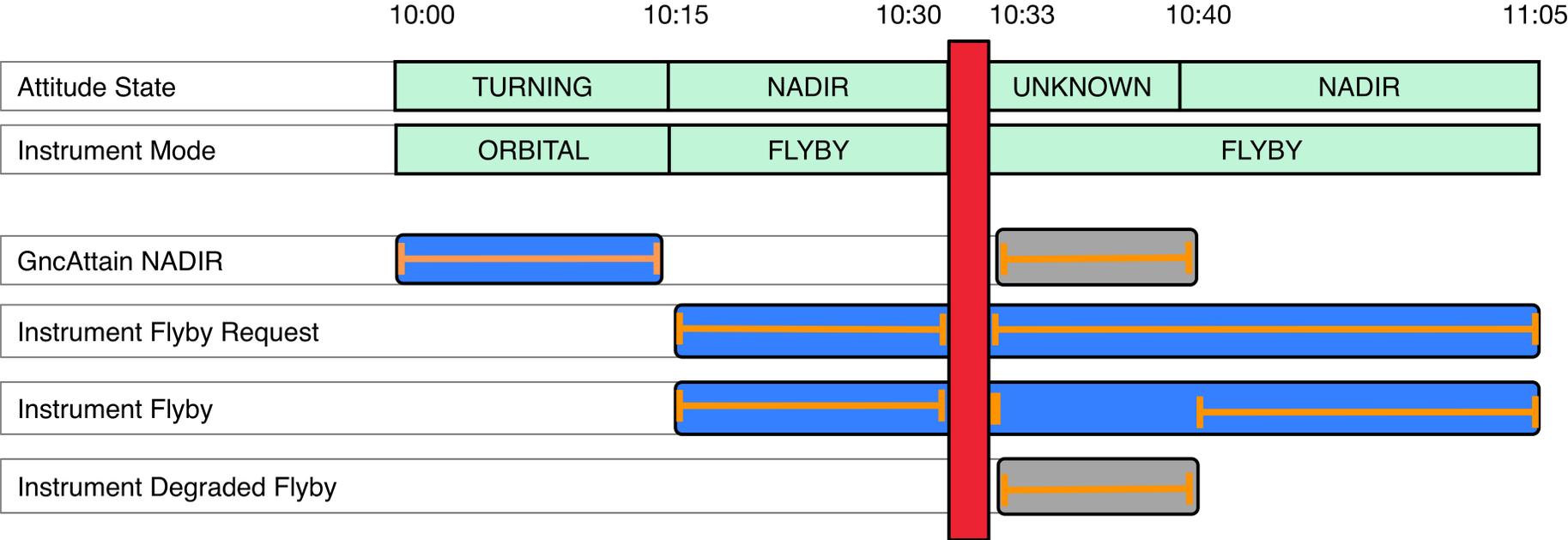
Gnc Attain NADIR:	POST IMPACT	Attitude State=NADIR
Instrument Flyby:	PRE CONSTRAINT MAINTAIN CONSTRAINT DURING IMPACT	Attitude State = NADIR Attitude State = NADIR Satisfies InstrumentFlybyRequest
Instrument Degraded Flyby :	DURING IMPACT	Satisfies InstrumentFlybyRequest

Example Contingency Response:
Restart InstrumentFlyby on failure

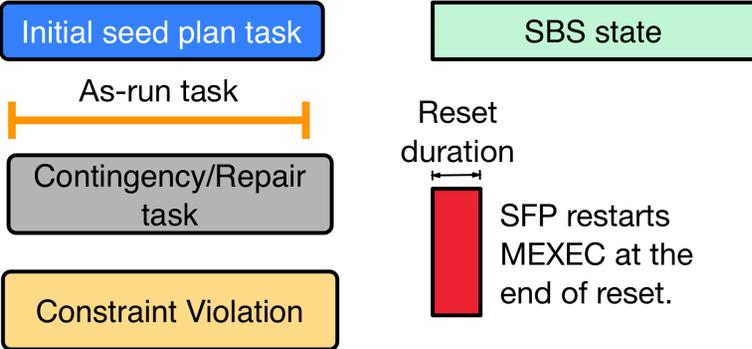
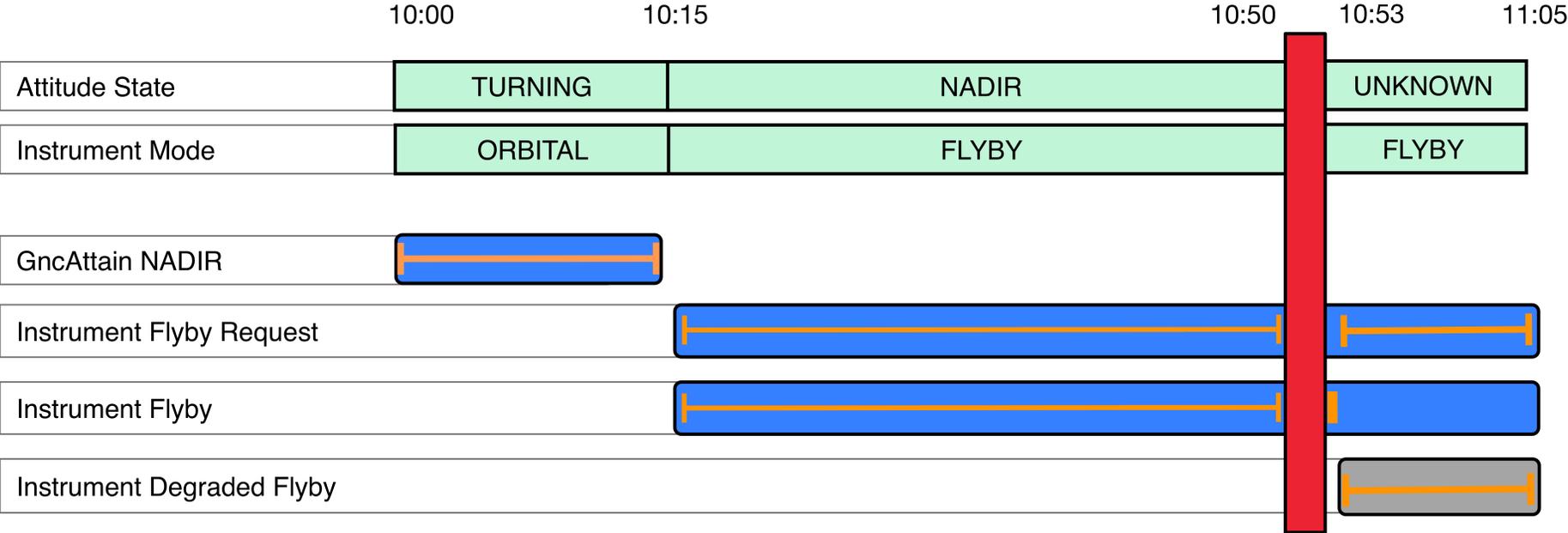
Example Plan Modifiers to resolve violation:
Add GncAttain NADIR
Add Degraded Flyby
Remove InstrumentFlyby



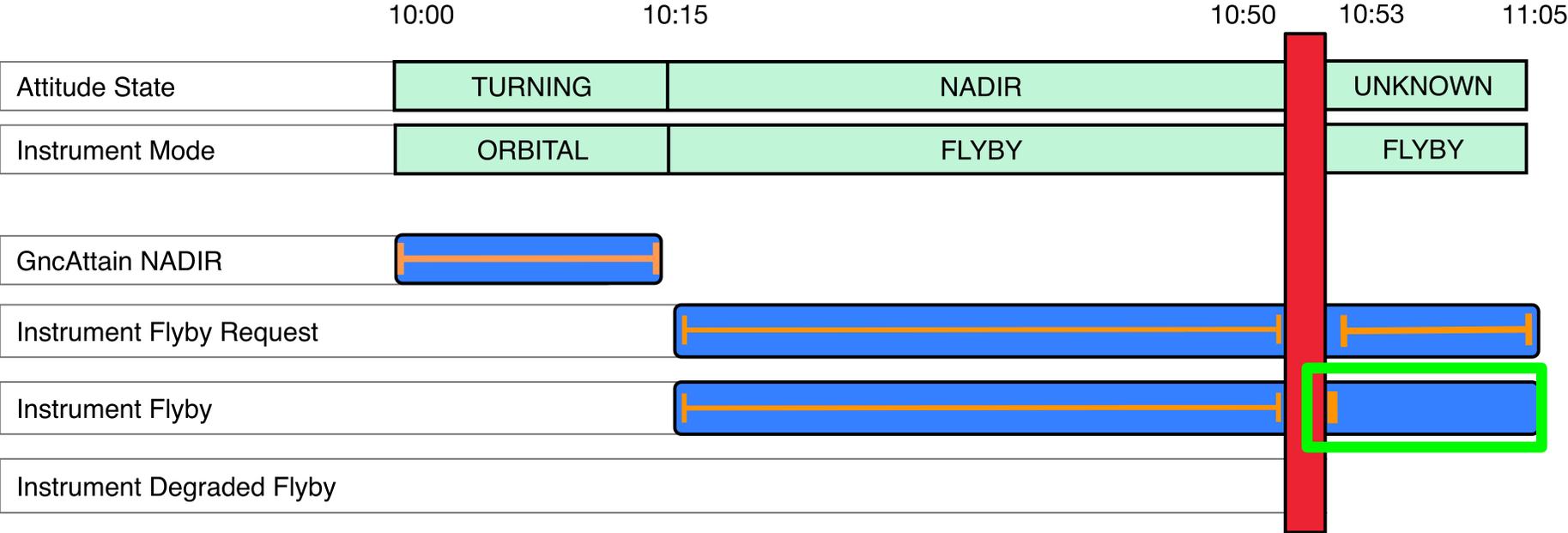
EXAMPLE: RESPONSE TO EARLY RESET



EXAMPLE: RESPONSE TO LATE RESET



EXAMPLE: RESPONSE TO LATE RESET

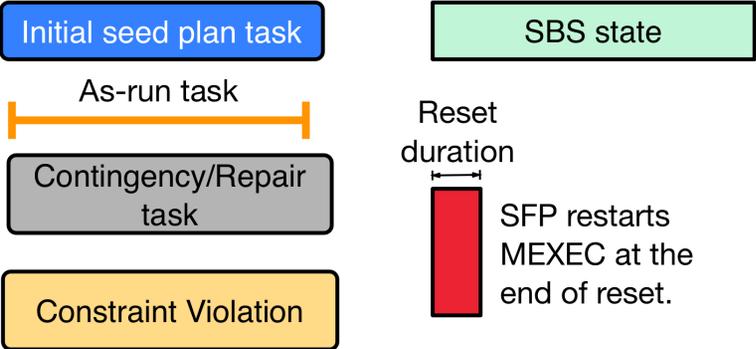


Example Task Constraints/Impacts:

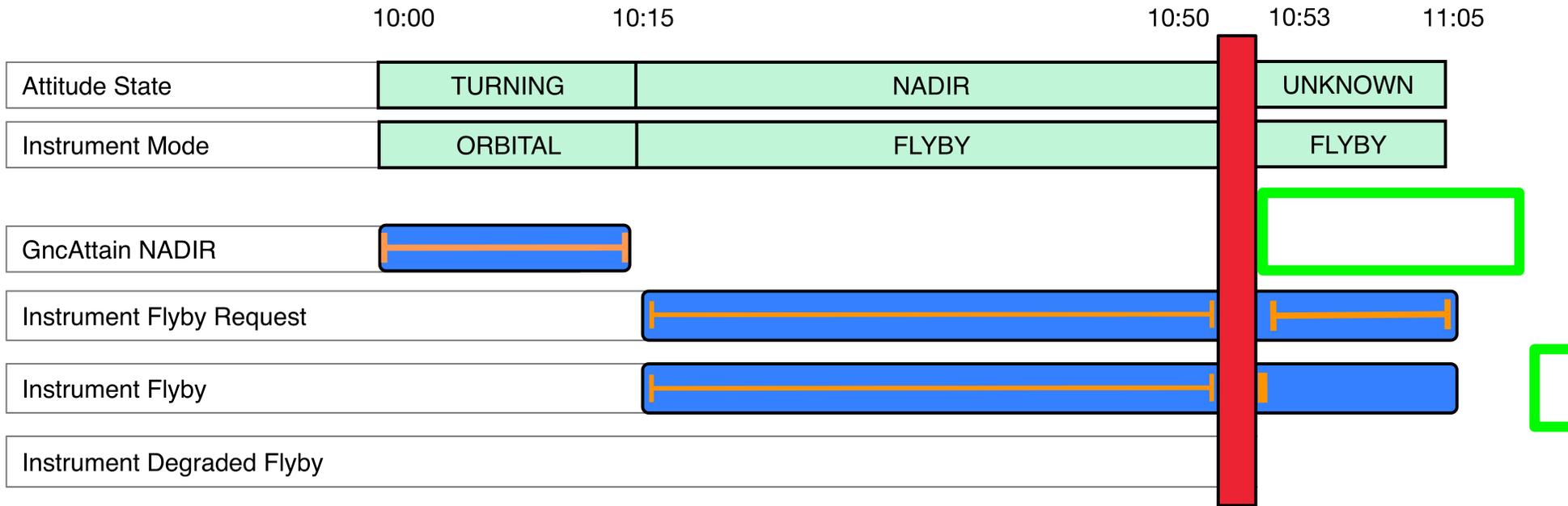
Gnc Attain NADIR:	POST IMPACT	Attitude State=NADIR
Instrument Flyby:	PRE CONSTRAINT MAINTAIN CONSTRAINT DURING IMPACT	Attitude State = NADIR Attitude State = NADIR Satisfies InstrumentFlybyRequest
Instrument Degraded Flyby :	DURING IMPACT	Satisfies InstrumentFlybyRequest

Example Contingency Response:
Restart InstrumentFlyby on failure

Example Plan Modifiers to resolve violation:
Add GncAttain NADIR
Add Degraded Flyby
Remove InstrumentFlyby



EXAMPLE: RESPONSE TO LATE RESET

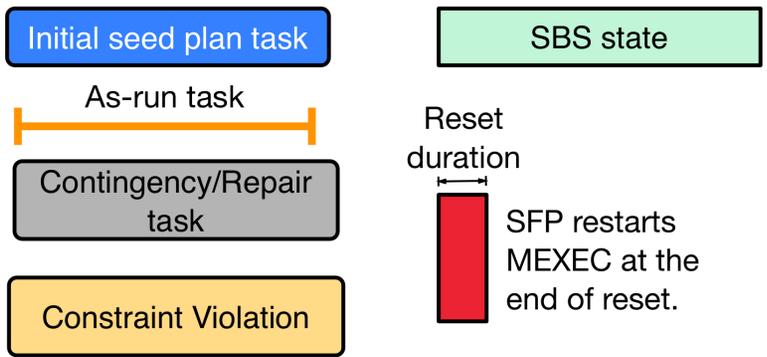


Example Task Constraints/Impacts:

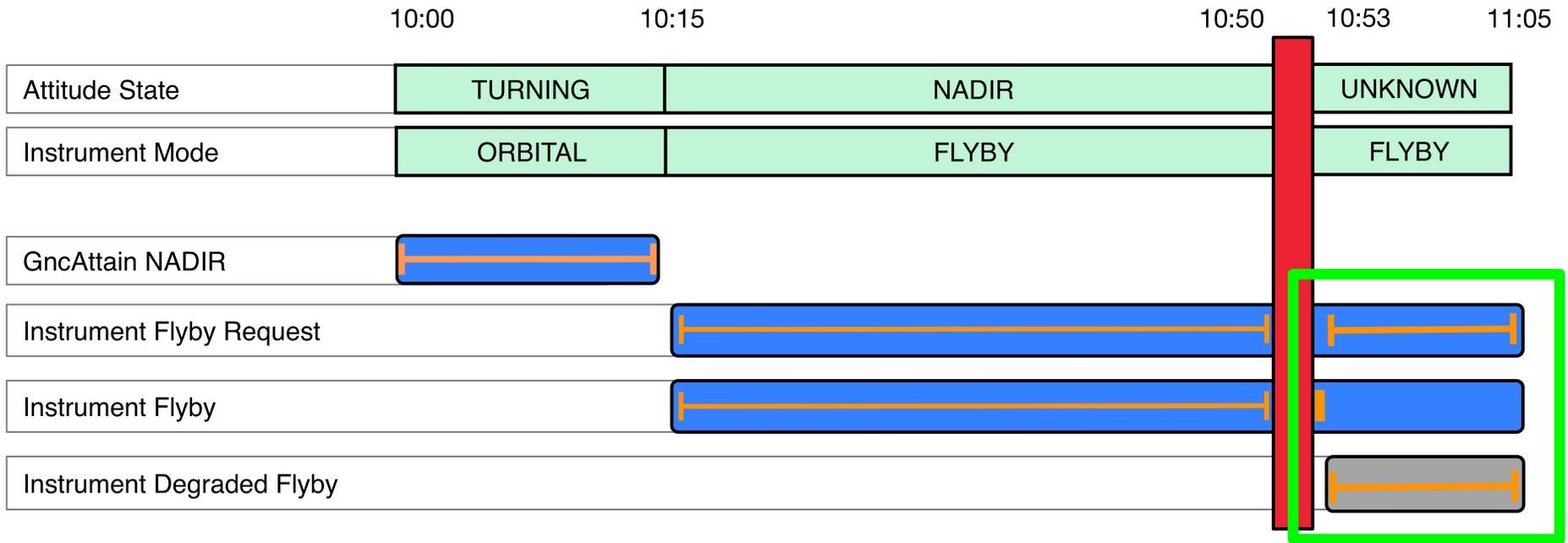
Gnc Attain NADIR:	POST IMPACT	Attitude State=NADIR
Instrument Flyby:	PRE CONSTRAINT	Attitude State = NADIR
	MAINTAIN CONSTRAINT	Attitude State = NADIR
	DURING IMPACT	Satisfies InstrumentFlybyRequest
Instrument Degraded Flyby :	DURING IMPACT	Satisfies InstrumentFlybyRequest

Example Contingency Response:
Restart InstrumentFlyby on failure

Example Plan Modifiers to resolve violation:
Add GncAttain NADIR
Add Degraded Flyby
Remove InstrumentFlyby



EXAMPLE: RESPONSE TO LATE RESET

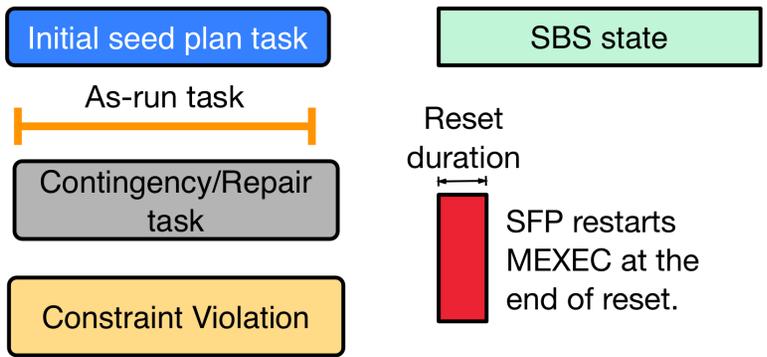


Example Task Constraints/Impacts:

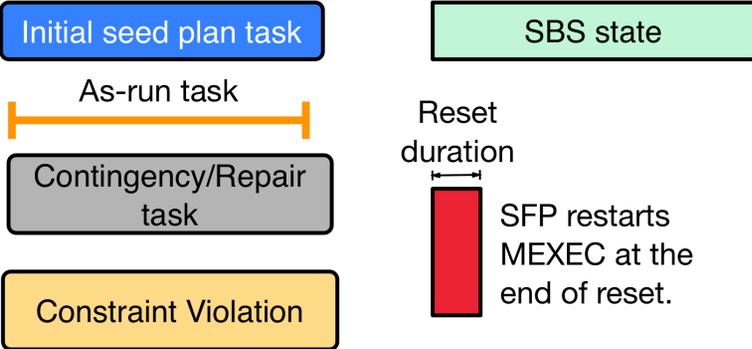
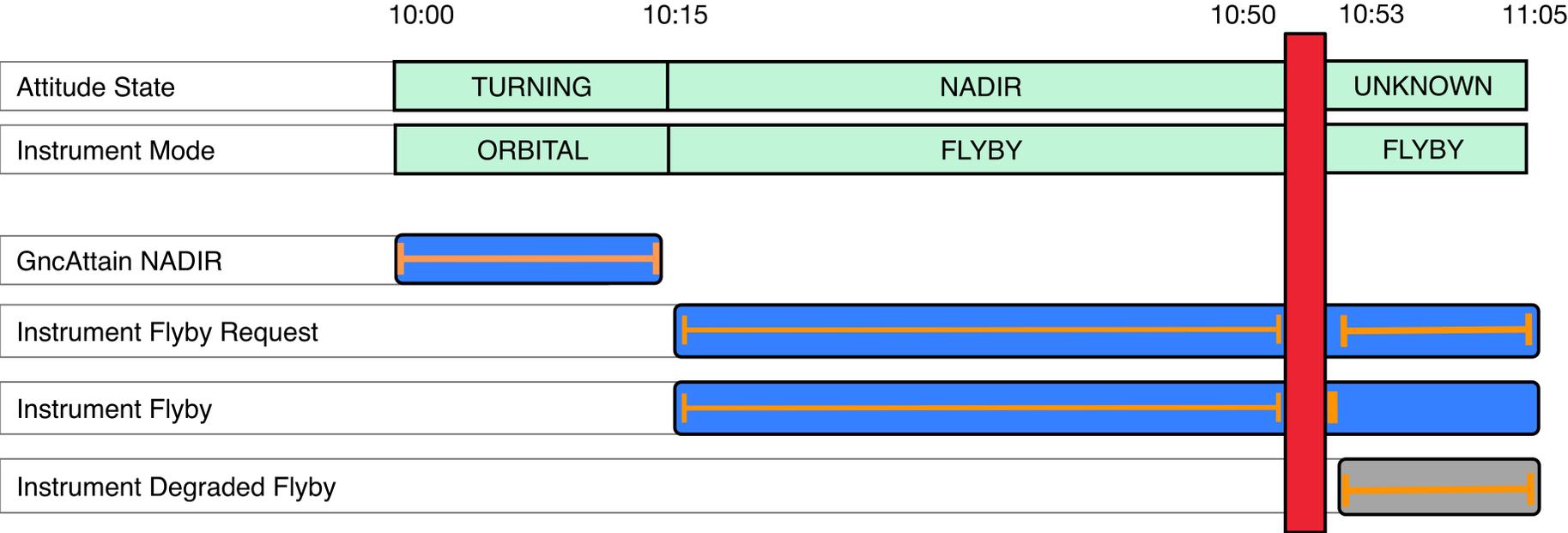
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EXAMPLE: RESPONSE TO LATE RESET



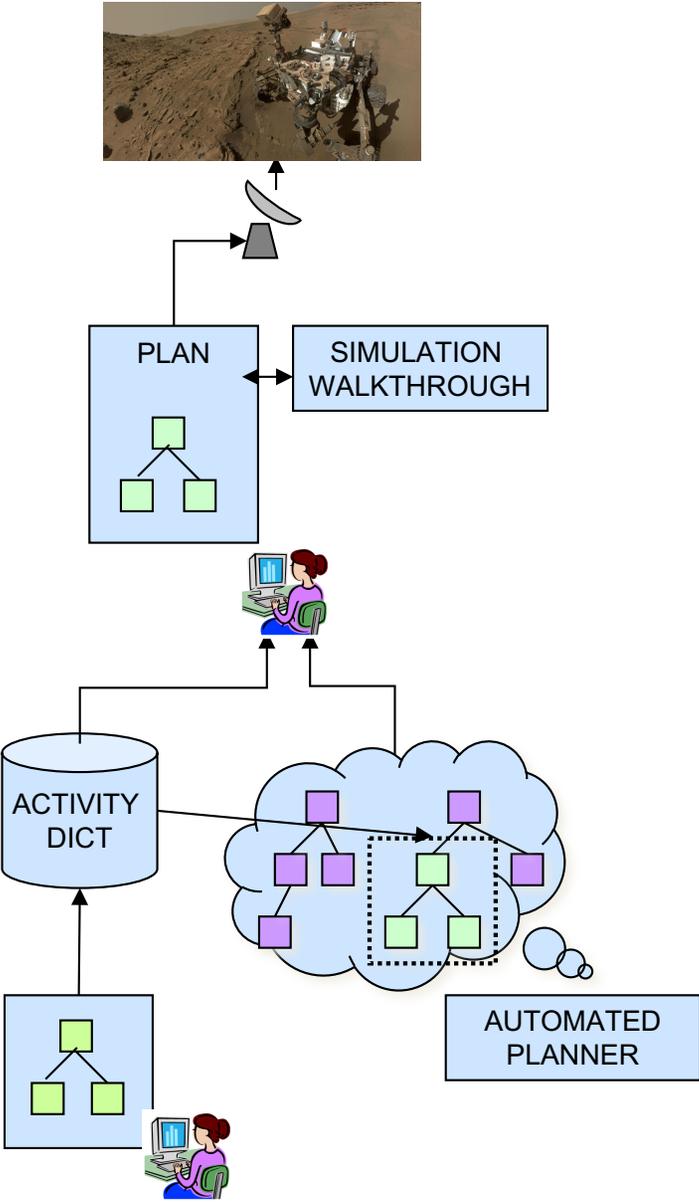
SUMMER 2016 PROTOTYPE DEVELOPMENT SUMMARY

- **Designed and implemented prototype version of MEXEC**
 - 11289 lines of C code, excluding auto-code, scenario support files, unit tests, standard FSW infrastructure
 - Designed for **multi-mission** use with few dependencies on Europa FSW or OS.
 - Part of MEXEC code was inherited by the M2020 simple planner.
- **Multiple fail-operational scenarios for Europa flyby**
 - Reset at different times while GNC is maintaining NADIR pointing for FLYBY science
 - Reset at different times while GNC is slewing for UVS Scan and UVS is Scanning
- **Demonstrated in Linux, WSTS and Europa flight system testbed**
 - Runs in WSTS and on testbed *with space and time partitioning*
 - *Takes less than 0.1 seconds to resolve plan problems after simulated reset in testbed*
- **Demonstrated ability to dispatch and monitor execution of FSW commands**
 - Simulated GNC, Thermal, and instrument flight software
 - Used Europa FSW Core command dispatch interface
 - Demonstrated option to provide task parameters as arguments to FSW commands
 - Used co-ordinated FSW State Buffer Store concept
- **Demonstrated end-to-end scenario with ground tool prototype**
 - Incorporated ground tool generated output as input to MEXEC

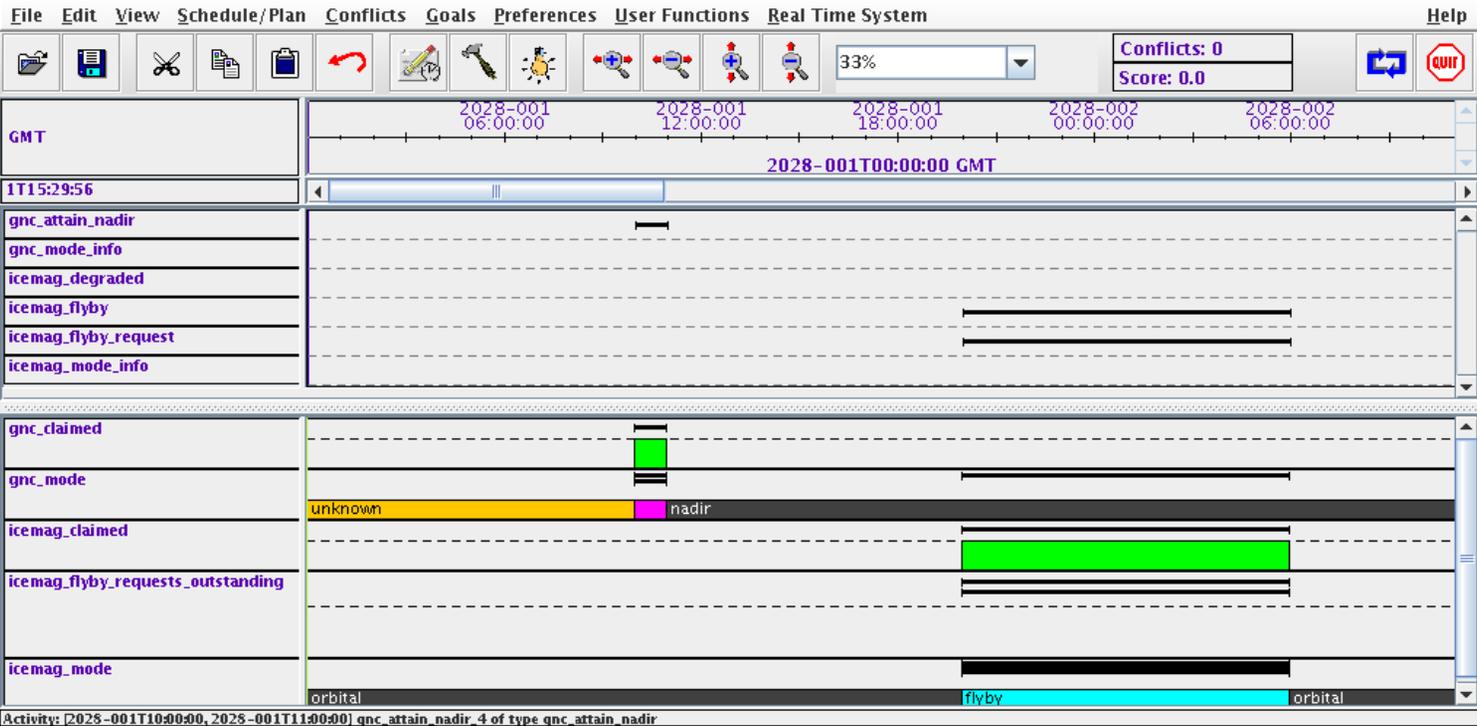
TASK/ACTIVITY DICTIONARY

- Used to define the default values for tasks: expected durations and constraints/requirements/relationships
 - Task instance can override defaults, add/remove constraints
 - Similar to existing flight operations activity dictionaries
- Defined on the strategic timeline, referenced (by ground tools) on the tactical timeline
- Uploaded in advance, for MEXEC to reference
- Easy to change when necessary (without FSW upload)

GROUND-BASED PLANNING MAY BE MANUAL OR MIXED-INITIATIVE



EXAMPLE GROUND TOOL: PROPOSED PLAN UPDATE



CONCLUSIONS

- Provides fail-operational capability
 - Constraints checked on-board for executing and remaining plan
 - Does not require special cases for FSW reset occurring at different times
- Provides plan enhancement option
 - MEXEC can add, move, and remove tasks if given permission
- Provided preliminary feasibility assessment for flight and ground
 - Integrated into Europa Flight Software. Parts ported to M2020 simple planner.
 - Demonstrated capability with time and space partitioning on Europa system testbed
 - Developed proof-of-concept ground tool to generate input to MEXEC using ASPEN planning and scheduling system
 - Demonstrated MEXEC execution with output from ground tool
- Lessons learned
 - Need to demonstrate validation of MEXEC plans - a key concern for operators
 - Need to develop user friendly interfaces to specify and manage MEXEC tasks